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# Evaluation of Soil Function Following Remediation of Petroleum Hydrocarbons—a Review of Current Remediation Techniques

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**Abstract**

*Purpose of Review* Management of lands contaminated by petroleum hydrocarbons (PHC) continues to evolve, as project goals may be shifting from contaminant reduction to ecosystem restoration. Restoring soil function is vital to overall ecosystem recovery, as soils perform numerous processes that are inhibited by PHC contamination. The purpose of this review is to summarize the effects of various remediation strategies on soil properties and evaluate how those effects relate to soil functions.

*Recent Findings* All remediation techniques alter soil function, and the extent of alteration is based on project-specific operational parameters. Broadly, most techniques alter soil organic matter (SOM) content and soil pH, which are important variables associated with many soil processes. Additionally, recent technological advances have made the characterization of soil microbial communities and activities more accessible, so the field continues to gain knowledge on how remediation strategies affect soil microorganisms that are vital in nutrient cycling and waste management.

*Summary* This review identified soil properties and functions that are likely to be affected by each strategy and that should be monitored following successful remediation. The extent of changes in soil properties is dictated by specific implementation of remediation methods, so general comparisons between methods may not be appropriate. While important variables like SOM and pH are valuable indicators of soil function, the dynamic relationships between all soil properties should not be overlooked following soil remediation. Thus, future research on soil remediation should strive to assess changes in how soils function, in addition to contaminant removal efficiency.

**Keywords** Soil remediation · Soil restoration · Bioremediation · Soil function · Petroleum hydrocarbon contamination · Crude oil spill

## Introduction

Soils perform vital ecological functions that provide services in both natural and anthropogenic systems [1–3]. Disturbances affect the soil's capacity to perform these functions, thus affecting overall ecosystem processes. One widespread disturbance is exposure to petroleum hydrocarbon (PHC) contamination during extraction, transportation, or storage of petroleum resources. In addition to posing a risk to human health, PHC contamination disrupts or inhibits many soil functions [4–7]. Therefore, remediation of the contaminant is required to reduce the risk of exposure, restore soil function, and provide ecosystem services.

Generally, many remediation strategies are available for contaminated soils [8–10], and these have been reviewed with specific focus on PHC contamination [11•, 12, 13]. These reviews identify the effectiveness of each strategy at reducing contaminant concentrations in different circumstances, as well as how to best optimize operational parameters for contaminant reduction. This information is vital for practitioners when choosing the appropriate strategy, as cleanup efficiencies may be affected by a myriad of factors, including extent of

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contamination, climate, location, soil properties, regulatory goals, and available resources [8, 11•, 14]. However, notably absent from these reviews is an in-depth discussion of the effects of these remediation strategies on the soil following contaminant reduction, a knowledge gap identified by several reviewers [10–12].

This body of literature reflects the traditional view of site remediation, wherein a contaminated site is assessed, remediated, reclaimed or restored, and monitored [15]. This linear approach to contaminated site management is challenged by recent research that pairs remediation with restoration and considers them concurrently [15, 16••, 17•]. In this context, remediation is defined as the removal or containment of contaminants, and restoration is defined as the recovery of ecosystem function in a damaged or disrupted area [15]. This approach requires clearly defined goals at the beginning of the decision-making process, as oftentimes steps taken during the remediation process may affect the subsequent restoration [16••]. Thus, understanding the impacts of each remediation strategy on soil function is critical in the decision-making process for each contaminated site.

## Assessing Soil Function

A difficulty in using soil function as an indicator of remediation or restoration success is that no single direct metric of overall "soil function" exists, especially given the variability of soils across time, space, and depth. Rather, it must be understood in the context of several functions that soils perform. These soil functions may be partitioned in many ways [1–3], but most sources agree on a common core of functions occurring in both natural and anthropogenic systems. Four soil functions are included in this review: (1) serving as suitable habitat capable of sustaining biodiversity, (2) providing structure and a resource medium for biomass production, (3) storing and filtering water resources, and (4) degrading, detoxifying, and managing wastes through both nutrient cycling and long-term resource storage. While not discussed in this review, soils also serve as an engineering medium for human development, provide cultural significance, and act as an anthropological tool [1, 2].

This range of functions demonstrates how soil is best understood as a series of dynamic, interconnected processes that are dictated by a combination of soil properties rather than a single metric. Due to this interdependence, manipulating any single variable will affect other soil properties, as well as the capacity of the soil to perform each of the functions. Despite the crucial role soils play in ecosystem restoration, many practitioners lack a deep understanding of how soils actually function [19], as evidenced by the fact that both remediation and restoration research often fail to adequately address soil metrics [18]. In the studies that do include soil metrics, the measurements are generally confined to singular properties, such as soil pH, soil organic matter (SOM), microbial biomass, or plant-available nutrients. Thus, research often omits the complex interactions and relationships that the properties have with each other, as well as how these properties affect overall soil function.

## Aims and Scope

The aim of this review is to highlight the importance of considering impacts of remediation activities on soil function, so this review may be used as a tool for remediation and restoration practitioners when choosing a specific technique. This review summarizes recent research documenting the effects of some established remediation strategies on soil properties and discusses implications for soil function. Notably, this review assumes that the direct effects of PHC contamination on soil function are alleviated at the endpoint of remediation, which varies widely from project to project. It includes no in-depth discussion of how soil parameters are affected through the course of the remediation project, but rather it considers the soil function at the completion of remediation. Thus, the review directly compares the remediated soils to pre-disturbance soils to determine the effects of each remediation strategy. This comparison reflects a high degree of restoration and may not be applicable in all situations, as each project will have varying targets for land use, productivity, and contaminant reduction. Further, the time required for recovery of soil function following remediation is widely variable, so specific discussion of temporal considerations is outside the scope of this review. Finally, the review targets soil function after remediation is "completed," but the definition of "completed" remediation may be site-specific and include considerations associated with risk management, such as contaminant type and future land use [95].

This review further narrows the scope to include only strategies commonly used to target terrestrial PHC contamination, although the nature of this contamination is widely variable. Numerous organic compounds are classified as PHCs, which include different grades of crude oil and refined fuel products, and the type of compounds often dictates the optimal remediation strategy [34]. The remediation techniques addressed in this review all target a range of PHCs, and these techniques are (1) bioremediation, (2) phytoremediation, (3) chemical oxidation, (4) surfactant extraction, (5) electrokinetic remediation, and (6) thermal desorption. This list does not include all remediation strategies, but rather it focuses on some established approaches that have accompanying literature assessing soil properties. Moreover, while each of these techniques is used for PHC remediation, the primary application may be for other types of contaminant (e.g., electrokinetic remediation is primarily applied to heavy metal contamination). Thus, the information provided in this review may be broadly applicable beyond PHC contamination. Further, many successful projects integrate several methods of remediation in a single project, but this review does not address each combination of methods. Finally, the review highlights how integrating remediation and restoration may be beneficial for practitioners.

## In Situ vs. Ex Situ Remediation

Remediation strategies may be classified as in situ, where treatment occurs in place, or ex situ, where contaminated soil is excavated prior to treatment. Many strategies described in this review can be applied both in situ and ex situ, but rather than address both in situ and ex situ impacts for each type of treatment, general effects of treating the soil in place are contrasted against soil excavation. Further impacts to soil properties from each individual treatment may be then considered additive to either in situ or ex situ impacts.

In situ treatment often results in some infrastructure construction and increased vehicular traffic [17•], but soil disturbance, especially relating to soil structure, is far less than excavation. However, in situ treatment offers less control over parameters that govern contaminant reduction, such as soil temperature, water, and aeration; thus, it is less reliable and takes longer, with projects often lasting month or years [8–10]. Two primary concerns for soil characteristics may be associated with in situ treatment. First, extended treatment times lengthen exposure of the soil to the negative influence of the contaminant. Second, as long as the contaminant remains in the soil matrix, a risk of migration exists. Further, without treatment, contaminants adsorbed onto SOM may be slowly released back into bioavailable forms through natural SOM degradation [20], effectively increasing the duration of exposure to the contaminant.

Ex situ treatment, on the contrary, allows for greater control over treatment parameters, so efficiency is higher and treatment times are typically shorter, with treatment times generally ranging from several weeks to several months. However, it requires excavation, more land for storage of excavated soil, and frequently, more infrastructure than in situ treatment [9, 11•, 17•]. Notably, the excavation and soil replacement process has extreme effects on soil properties. Existing soil structure is destroyed during excavation, so pore networks are completely altered following replacement. Further, the process reduces soil organic carbon (SOC), as mechanical disruption breaks down soil aggregates and mineralization increases to release more $CO_2$ into the atmosphere [21–23]. Thus, these excavated soils are more susceptible to compaction induced by the heavy machinery that is required for large-scale excavation [24, 25].

This compaction has some deleterious effects on soil properties and soil function. First, compaction reduces infiltration [26], which increases runoff and surface erosion. Further, the loss of a diverse pore size distribution and pore connectivity in compacted soils results in slower water movement within the soil profile [27]. Recovery of pore networks is slow, since compaction may inhibit processes and activity of organisms that create them, such as root elongation [28] and soil macrofauna [29, 30]. In some cases, the smaller pores can promote microorganism activity and increase respiration and N mineralization [31, 32]. However, a bulk density value of 1700 kg $m^{-3}$ may indicate a threshold above which most biological indices decline [32]. Thus, excavation and soil replacement may have substantial impact on soil function, and any additional impacts of other remediation strategies could exacerbate those effects.

## Bioremediation

Bioremediation is a process wherein soil organisms reduce contaminant concentration through degradation, detoxification, stabilization, or transformation [33], and it is commonly implemented both in situ (e.g., natural attenuation, bioventing) and ex situ (e.g., landfarming, composting). The principle of this technique is to optimize soil parameters that govern the rate of biodegradation, namely, soil temperature, moisture, porosity, pH, C:N ratio, available nutrients, redox potential, and microbial populations, diversity, and activity. These parameters may be optimized for an indigenous microbial community (biostimulation) or for an introduced contaminant-degrading community (bioaugmentation). Generally, bioremediation requires less resource input than other techniques, and it is perceived as an environmentally friendly approach. Further, in large-scale PHC contamination sites, as well as those with low risk for contaminant migration, natural attenuation, coupled with risk management, is often determined to be the most practical solution. However, bioremediation is often slow and unreliable, and thresholds of toxicity to microorganisms may preclude its use in some circumstances [11•].

### Impacts on Soil Properties

The specific impacts of bioremediation may vary slightly based on the method of implementation; some reviews [33, 34] offer descriptions of each method, as well as advantages and disadvantages. The most common consequence of bioremediation is the accumulation of toxic compounds formed by incomplete degradation of PHCs [35–39]. These intermediate products, which usually are not identifiable by traditional total petroleum hydrocarbon (TPH) or polycyclic aromatic hydrocarbon (PAH) tests, may still cause soil toxicity [35]; therefore, these tests may not be the best indicators of remediation success. For example, naturally attenuated soils that met Australian safety guidelines for TPH levels still exhibited toxicity to earthworms and radish plants [39]. In a bioaugmentation study, intermediate degradation metabolites initially decreased wheat growth and increased ecotoxicity; ecotoxicity began to decline after 24 days, although it persisted throughout the 40-day study [38•]. Similarly, the accumulation of these products has led to increased cytotoxicity in bioreactor treatments [36, 37]; however, the bioavailability of these compounds was very low following bioreactor treatment, so the immediate risk was reduced.

Beyond increased soil toxicity, further effects of bioremediation on soil properties are dictated by the addition and incorporation of organic amendments (e.g., composting) because SOM (which is comprised of 50–58% SOC) is so valuable in regulating many soil characteristics [40]. Increasing SOM through application of compost increases aggregate stability, porosity, and water holding capacity [41], as well as reduces susceptibility to compaction. Although few bioremediation studies identified these parameters, these benefits may be assumed on remediation projects that increased SOC [42–44, 45•]. Further, microbial degradation rates of organic compounds increase as SOM increases. This degradation forms residual acidic products, so pH is also affected by SOM dynamics.

A landfarm project incorporating cotton stalks in the soil increased SOC from 2.33 to 6.74%, which accompanied a drop in pH from 8.6 to 7.1 [42]. Similarly, biopiles inoculated with a microbial consortium and sawdust had greater degradation of TPHs (80%) and lower pH (6.5) than those without sawdust (33%; 7.2) [43]. However, mechanical agitation often employed in bioremediation projects may contribute to SOC loss, as even a non-contaminated treatment in a biopile study had SOC decrease from 4.6 to 2.8% after 400 days [47]. Therefore, applying organic amendments may not only be a valuable way to encourage bioremediation and regulate soil pH, but it may also be necessary to retain SOC levels. This need is evident in a landfarm project that did not add compost, in which SOM decreased up to 40% and soil pH increased from 7.3 to 8.3 [46].

### Implications for Soil Function

The accumulation of incomplete metabolites of PHC degradation has been shown to harm vegetation and soil macrofauna [38•, 39], but soil microbial communities do not appear to be as sensitive. Compost application to PHC-contaminated soil in a laboratory incubation resulted in a 400% increase in basal respiration and 200% increase in phosphatase and beta-glucosidase enzyme activities [45•]. Similarly, heterotrophic bacteria increased up to 200% in landfarm soil fertilized with N, P, and K compared to the control [46]. In conjunction with increased respiration and biomass, the Shannon index of microbial community diversity increased from 1.4 to 3.6 in a landfarm soil with organic amendments [42]. The inundation of resources from composting, aeration, irrigation, and fertilization greatly increases soil microbial abundance and diversity, despite increased toxicity levels.

Recent studies have been able to tie these broad microbial metrics to specific shifts in microbial community composition. In a comparison of methods, the primary hydrocarbon degraders in biopiles were *Alpha-proteobacteria*, whereas bioslurry treatments were dominated by *Gamma-proteobacteria* [49]. A laboratory incubation study found another distinction in microbial communities, wherein oil-contaminated soil with added compost contained 50% more gram-positive bacteria, while gram-negative bacteria were more prevalent in non-compost soils [45•]. These shifts show dominance of organisms that thrive in more extreme environments (e.g., gram-positive bacteria), but the impacts to soil functions are unclear. Perhaps future advances in these techniques can elucidate the impacts of these community shifts, but in these studies, no clear indication of inhibition of soil waste management or nutrient cycling was identified.

In addition to these biological implications, bioremediation also changes the hydrologic functioning of the soil, especially in methods with compost amendments. The application of SOC improves water-stable aggregation and porosity [50], thereby increasing water holding capacity and infiltration, as well as decreasing erosion. Thus, composting encourages both soil fauna and vegetation by allowing greater access to both water and essential nutrients. However, very high concentrations can harm water quality, as compost application at 5% *w*/*w* increased water-soluble carbon from 12 to 33 mg $\text{kg}^{-1}$ [45•]; similar increases in other nutrients could exceed the soil's ability to filter and protect water resources.

## Phytoremediation

Phytoremediation is a bioremediation technique in which vegetation is used to remove, detoxify, or stabilize organic contaminants in soil [12], and it includes the processes of phytoextraction, phytostabilization, phytovolatilization, phytodegradation, or rhizodegradation [11•]. This method may be especially appealing to remediation practitioners because it employs soil function (e.g., biomass production, waste management) to reduce contaminant concentration. However, like other bioremediation options, phytoremediation is slow, has varying success at removing contaminants, and it cannot be applied at very high concentration levels at which plant growth may be diminished or even absent. Further, the benefits of phytoremediation are generally confined to the root zone, so the depth of treatment is dependent on the rooting structure of the vegetation.

### Impacts on Soil Properties

Since phytoremediation is a specific type of bioremediation, most of the effects on soil properties and functions discussed in the bioremediation section also apply to phytoremediation.

However, vegetation production is associated with additional alterations to soil properties. Notably, root growth improves porosity, and root exudates can stimulate aggregate formation [51]. These aggregates may stabilize SOM in phytoremediation sites, as dissolved organic carbon (DOC) decreased under a range of operating conditions [52–54]. Similarly, phytoremediation may decrease mobility of contaminants and heavy metals in the soil through the process of phytostabilization [11•]. Vegetation is generally associated with increasing SOM, which typically results in lower soil pH. However, this trend does not hold true in all phytoremediation studies. Soil pH increased from 5.7 to 7.1 in PAH-contaminated soils producing alfalfa [53], as well as in fuel-contaminated soils growing galega (*Galega orientalis*) (from 5.7 to 6.2) [52], suggesting a neutralizing effect on soil pH of acidic soils.

The improved physical and chemical properties for soil microorganisms are also supplemented by root exudates that stimulate microbial growth [55]. This growth may occur rapidly, as soil microbial biomass doubled from 2 to 4 $\mu g\ g^{-1}$ in 7 weeks in soils growing galega, which corresponded with increased enzymatic activities [52]. Similarly, microbial biomass in soils growing alfalfa [53] and wheat [56] increased by several orders of magnitude (CFU $g^{-1}$ soil). Interestingly, the community composition did not shift to favor TPH degraders in either case, indicating that the numbers already present in the soil were sufficient for contaminant degradation.

### Implications for Soil Function

Due to the synergy of plants, soils, and microorganisms [55], soil function is generally improved during treatment, although few studies offer direct comparison to non-contaminated soils. Notably, many of these studies utilized phytoremediation either as a secondary treatment or as a strategy for low amounts of contamination. Thus, declines in plant growth or increased toxicity to organisms were attributed to conditions caused by soil properties (e.g., high electrical conductivity (EC), low pH) rather than contamination [53]. However, in sites where contamination was likely the cause for reduced plant production, contaminant reduction resulted in greater biomass production [52, 56], indicating that these soils' suitability for vegetation was increased by phytoremediation. Thus, increased vegetative production improves soil properties, which improves contaminant reduction, which improves vegetation production; this positive cycle typifies a successful phytoremediation project.

The increased porosity and aggregate stability accompanying root growth improve soil structure to allow for better transport of water, oxygen, and nutrients for soil organisms and root uptake. This access to resources is a primary cause for the increase in soil microorganism populations, and it does not seem to be accompanied by a shift in community composition [53, 56]. Therefore, typical nutrient cycling and organic compound degradation may be expected to continue in these soils. Further, the presence of roots, in conjunction with an overall increase in SOM, serves to intercept nutrients from the soil solution, reducing losses associated with leaching.

Nonetheless, a primary concern for phytoremediation strategies, as with any in situ treatment, is migration of contaminants in the soil profile, as treatment may take several months or years. The propensity of a contaminant to migrate is widely variable, as it is based on its own characteristics, especially solubility, cohesion, and adhesion, as well as the soil characteristics, especially moisture content, texture, and SOM [57]. For example, fuel compound mobility was low when applied to pure montmorillonite or topsoil, but the addition of some root exudates to both increased contaminant mobility [58]. These responses may have been based on the effect of root exudates on soil pH, wherein carboxylic compounds decreased pH and increased mobility whereas phenolic compounds increased pH and reduced mobility.

## Chemical Oxidation

Chemical oxidants can be applied to contaminated soil to convert hazardous compounds into nonhazardous products. This technique can be applied in situ by injecting an oxidant into the contaminated matrix or ex situ in more controlled conditions. The most common oxidants used in soil remediation are Fenton's reagent (hydrogen peroxide and iron catalyst) and permanganate [59, 60], although other oxidants are also used, such as ozone [61] or persulfate [62]. Chemical oxidation may be widely applied because it is not affected by highly toxic environments, and it is capable of targeting non-biodegradable compounds [11•], although it may be expensive and leave residual products.

### Impacts on Soil Properties

Two major impacts to soil properties are evident following chemical oxidation, regardless of which oxidant is applied. First, soil organic matter is degraded, the extent of which is dictated by dosage and mode of application. The degradation is expected because Fenton's reagent involves the application of hydrogen peroxide, which is often employed to remove SOM in soil analyses [63]. Thus, application of Fenton's reagent can result in an 80% reduction of SOM at doses of 0.14 mol $L^{-1}$ [59] or 160 mL of 4 M $H_2O_2$ [60] in slurry reactors. However, in unsaturated conditions, similar dosages reduced SOC by less than 10% [64]. Both ozone [61] and permanganate [59] also reduced SOM by up to 50%, depending on dosage. Notably, this reduction of SOM is accompanied by a dramatic increase in DOC in the soil solution [59–61]. Further, chemical oxidation may preferentially target SOM before any organic contaminants, thus ensuring that

SOM may be depleted before contaminant removal occurs [Baker, JM, personal communication, 2017 Feb 27].

The second major impact of chemical oxidation is the alteration of soil pH. Fenton’s reagent requires very low pH (around 3), which is a dramatic decline in most soils. Correspondingly, oxidation with Fenton’s reagent reduced pH from 7.2 to 3.2 in a slurry [59] and from 7.3 to 4.9 in dry soil [64]. Conversely, pH increased up to 9.8 using permanganate [59]. This alteration in pH, especially using Fenton’s reagent, increases the solubility of some metals, such as Zn, Cu, and Mn [59, 60], which may make them more bioavailable to vegetation and soil fauna or eventually impact water quality. Further, application of Fenton’s reagent greatly increases the extractable Fe concentration in soil [59]; however, the availability diminishes when soil pH is increased. The high quantities of Fe applied to the soil may also precipitate soil P to form iron phosphates, which should be considered when applying P to these soils. However, some research suggests that use of chelating agents may allow chemical oxidation to occur at existing soil pH, mitigating some of these consequences [65•, 66].

### Implications for Soil Function

These major alterations to SOM and pH affect the soil’s ability to sustain biological communities following chemical oxidation, especially as some oxidants (e.g., ozone, peroxide) are also disinfectants. Following Fenton’s reagent application, microbial number and density decreased by more than 90% [64], although they recovered after 35 days. Similarly, application of permanganate and hydrogen peroxide at 5% *w/w* dramatically reduced total bacteria count (more than 99%), but the counts recovered after 120 days [62]. Bacteria counts did not recover following persulfate application, even at 1% *w/w*. These declines may be the direct result of toxicity, or they may be caused by the change in pH or loss of resources with diminished SOM. Nonetheless, biological communities seem to recover once the oxidant is depleted. These studies did not investigate changes in community composition, but the recovery of overall metrics indicates that the soils likely retained capacity for nutrient cycling and waste management.

Similarly, vegetation is negatively affected by these changes in soil properties. Following Fenton’s reagent treatment, ryegrass germination was delayed with high treatment dose and reduced overall [64]. Compared to untreated soil, root and shoot biomass were significantly decreased at higher dosages (65 g kg$^{-1}$), but not at low dosages (6 g kg$^{-1}$). In another study using ryegrass, germination and aboveground biomass production declined with increasing Fenton’s reagent dose, with the highest dose (1.12 mol l$^{-1}$) producing only about 55% of the lowest dose (0.14 mol l$^{-1}$) [59]. Notably, ryegrass produced substantially less biomass in permanganate-treated soils at low dosages, and it did not germinate when permanganate concentration increased above 0.1 g l$^{-1}$. This finding was attributed to the precipitation of residual $MnO_2$ that clogged soil pores, altered water availability, and created anaerobic conditions [59].

Conversely, in most cases, the loss of SOM causes reduced water holding capacity and aggregation, which may increase leaching of DOC and other applied nutrients. This propensity for leaching may be especially detrimental following chemical oxidation due to the mobilization of heavy metals with the decrease in pH [59, 60]. Not only would water resources be threatened by this leaching but also the soil solution may contain increased amounts of heavy metals that are detrimental to microbial and vegetative growth.

## Electrokinetic Remediation

Electrokinetic remediation is typically an in situ process wherein an electric field is applied to contaminated soil by passing a direct current through anodes and cathodes inserted in the soil. This technique encourages contaminant movement to the electrodes by electroosmosis, electromigration, and electrophoresis [67]; of these, electroosmosis, the fluid flow of the soil solution caused by a charge gradient, is the most dominant [11•]. Electrokinetic remediation has been traditionally applied to inorganic contaminants (heavy metals), although recently the technology has also been applied to organic contaminants [68–72]. This technique is applicable in all soil types, especially low permeability soils, since electroosmotic flow is constant and not dictated by pore networks [11•].

### Impacts on Soil Properties

A ubiquitous consequence of electrokinetic remediation is the creation of a pH gradient between the anode and cathode in the soil [68–72]. The process causes electrolysis of soil water, creating $H^+$ and $OH^-$ ions that congregate near the electrodes, causing the soil pH to drop near the anode and rise near the cathode. The magnitude of this change may be moderate, ranging from 6.5 to 8.5 when a charge potential difference of 2 V cm$^{-1}$ was applied [69], to extreme, from 3.5 (anode) to 10.8 (cathode) when 0.63 mA cm$^{-2}$ was applied for 25 days [70]. The range of pH gradient is dictated by starting pH, current applied, soil water, and duration of remediation.

The process is also accompanied by a change in bioavailability of heavy metals. Most studies are not able to distinguish the cause of increased metal availability, as it may be the result of the direct current or the change in pH; regardless of the cause, electrokinetic remediation redistributes these metals. Cd and Zn accumulate near the anode, while Cu accumulates near the cathode [69, 72]. Essential plant nutrients may also be mobile in the soil following application of the electric field. In one study, soil N increased by 150% at the anode and decreased by 30% at the cathode [68]. Similarly, P accumulates at the anode, while K migrates toward the cathode [68, 72].

### Implications for Soil Function

The redistribution of soil resources, typified by the pH gradient, may be expected to create a spectrum of soil function across the treated area. Broadly, soil bacterial and fungal populations, as well as microbial respiration, were greatly diminished following treatment of 3.14 A $m^{-2}$ for 36 days [71]. However, the spatial distribution of microbial parameters, especially respiration, showed the greatest decline in acidic soil near the anode. Other studies have also found that bacterial abundance is negatively affected by electrokinetic treatment across an entire treatment area [70, 73], but, in some cases, the reduced total numbers are not associated with reduced enzymatic activity [69] and may sometimes be accompanied by increased activity [70]. These contradictory findings highlight the difficulty in finding a representative sampling location when these gradients are created. Nonetheless, microbial abundance and diversity follow the spatial trends caused by electrokinetic treatment, creating hotspots of nutrient cycling and SOM degradation.

Despite the accumulation of nutrients in some areas, electrokinetic treatment can have direct adverse effects on plant growth. Root elongation was decreased up to 25% in *Brassica juncea* when exposed to a charge potential difference above 2 V $m^{-1}$ [59]. Additionally, the depletion of N in other areas, in conjunction with increased heavy metal concentrations, likely implies reduced vegetation production and biological activity. Although no studies have identified long-term trends in these sites, the spatial distribution of resources caused by the initial migration would likely be reinforced by reduced plant growth and resource turnover near the treatment boundaries. Further, the mobility and accumulation of heavy metals [69, 72] may increase risk of adverse effects to water resources.

## Surfactant Extraction

Surfactants can be used to separate contaminants from the soil particles by dissolution, and they are commonly used in two ways in soil remediation. First, low concentrations of surfactants can be applied to the soil solution to enhance bioremediation by increasing contaminant bioavailability [48]. Second, high concentrations of surfactants may be applied to extract contaminants from soil particles in a washing (ex situ) or flushing (in situ) process. In washing processes, soils are saturated with water and mechanically agitated to concentrate the contaminants in the leachate or very fine soil particles [74]. Because these methods rely on the solubility of contaminants, attaining high cleanup levels of PHC using water is difficult due to the hydrophobic nature of many compounds. Thus, surfactants, such as Tween80 [75], TritonX-100, and Brij30 [76], are often added to reduce surface tension of the aqueous solution, which increases solubility of organic contaminants and encourages separation of contaminants from soil particles [12]. Although this extraction may rapidly remove contaminants from soil particles, the contaminated leachate must be treated by a secondary system.

### Impacts on Soil Properties

Recent work on surfactant extraction has focused on identifying the least toxic surfactants to apply for each specific contaminant. Therefore, surfactant extraction of organic contaminants is often done with only a few synthetic surfactants, usually nonionic (e.g., Tween80), and biosurfactants, which generally have lower toxicity levels [75–78], although many other types of surfactants, including anionic, are also commonly used [94]. When using these types of surfactants, soil physical and chemical properties are typically not altered. However, in some cases, surfactants show preference for sorption onto SOM and clay surfaces over the contaminant, so pore structures can be altered [78, 79]. Further, since ex situ chemical extraction is typically accompanied by some soil washing technique, changes to physical properties are likely to occur at this stage. The pretreatment of soil for washing includes mechanical agitation and screening [74], which can result in the separation of fine particles. Using this method, sand content can increase from 76 to 83% or from 40 to 87%, depending on soil type [80].

### Implications for Soil Function

Although little work has been done identifying direct effects of surfactants on soil physical and chemical properties, many studies have assessed the effects on soil biological properties. In a comparison of three surfactants, Tween80, TritonX-100, and Brij30, indices of an important gram-negative PAH degrader, *Sphingonomas sp.*, showed most inhibition by Brij30 and least inhibition by Tween80 [75]. In a similar study, both TritonX-100 and Brij30 applications increased total bacterial growth but inhibited archaea [76]. However, bacterial community composition changed, wherein only *Pseudonomonas sp.* remained at levels similar to non-surfactant applied soils. Overall, increased concentrations of most surfactants result in deleterious effects on the microbial community [75, 77]. One exception is Tween80, in which increasing concentration led to larger microbial populations [77]. This increase is likely due to the ability of soil microorganisms to utilize Tween80 as a sole carbon source. Nonetheless, despite utilizing more environmentally friendly surfactants, most still have negative impacts on microbial abundance, community composition, and activity. Again, the impacts of these biological changes to soil functions have not yet been examined.

In addition to direct effects on soil microorganisms, the physical pretreatment that often accompanies surfactant extraction removes fine soil particles [80], which results in less reactive surface area for water and nutrient transport in the soil. The reactive surface area is further decreased by the sorption of surfactant onto the SOM [78] and leads to decreased water holding capacity and cation exchange capacity (CEC). The adsorbed layer also decreases pore size, causing diminished permeability of both water and soil air [79]. Thus, even when the surfactants are not directly toxic to soil organisms, they may create conditions that inhibit biomass production or nutrient cycling.

## Thermal Desorption

Thermal desorption (TD) is a remediation technique that involves heating contaminated material (100–600 °C) to enhance the vaporization of contaminants, effectively desorbing them from soil particles. Since this process only separates contaminants from the soil, it is normally coupled with a secondary treatment, such as a thermal oxidation chamber [8]. TD may be used to target a wide range of organic compounds, as well as mercury, due to the ability to optimize heating temperature and time to each specific project [81–84]. One advantage of TD is its relatively short treatment time compared to other methods, although it has high costs due to energy requirements.

### Impacts on Soil Properties

The extent of the impacts of TD on soil properties and soil function is dictated by the heating temperature and duration. For all heating temperatures, the most notable consequence of TD is the combustion of SOM. Following TD treatment for 10 min, SOC decreased between 15 [84] and 25% [81] when heated to 350 °C, and it decreased by about 35% at 600 °C [85]. By extending the treatment time to 1 h, treatment at 350 °C decreased SOC by 85% [81]. However, reducing the treatment parameters to 200 °C for 15 min caused only about a 10% SOM reduction [83•]. At temperatures between 105 and 250 °C, this destruction of organic matter is accompanied by a flush of available inorganic soil nutrients that had been previously bound in the SOM [82, 86••].

Soil pH increases following TD treatment. The increase may be slight (6.5 to 6.8) at lower temperatures (200 °C) [83•], but pH can increase from 6.9 to 9.0 when treated at 360 °C for 1 h [82]. The magnitude of change is primarily dictated by the destruction of organic acids and release of cations from the SOM during combustion [86••]. In addition to increasing the pH, the release of some of these cations can increase soil EC. EC increased from 0.5 to 4 dS $m^{-1}$ when soil was heated above 300 °C [82], although other studies identified less drastic increases [86••], or even decreases in EC [83•]. Finally, the heating is associated with the release of heavy metals, as heating at 350 °C increased Al levels from 18 to 124 mg $kg^{-1}$ and Fe from 0.1–85.5 mg $kg^{-1}$ [85].

### Implications for Soil Function

Generally, TD-treated soils may be suitable habitat for a range of bacteria, mesofauna, and macrofauna [84] when compared to contaminated soil. Bacterial populations can reestablish quickly following the initial treatment, but enzymatic activities may remain low, which could be associated with reduced nutrient availability and changes in SOM quality [87]. Further, microbial diversity can be much lower following TD treatment. Following TD treatment at a PAH-contaminated coking plant site, the communities remained dominated by PAH degraders even 2 years after PAHs were removed [88]. However, after 2 years at the same site, fungal community structure was not affected and abundance recovered was comparable to untreated soil [89]. However, the increased heavy metal availability [85] may prevent TD-treated soils from fully recovering to pre-contamination levels. Recovery of soil fauna may vary among species, as increased genotoxicity in earthworms was attributed to bioavailable metals [90], although *Collembolae sp.* were not affected [84].

The effects of TD on plant biomass production may also be species-specific, as a study of 16 rangeland plants demonstrated varying levels of germination following TD at 500 °C [91]. Additionally, biomass of fescue and radish significantly differed following TD treatment at 350 and 600 °C [85]. At 600 °C, they produced roughly the same biomass, whereas at 350 °C, fescue produced 500% more than the radish. When soil was heated to 200 °C, *B. juncea* germination was only about 20% compared to unheated soil, and above ground length was reduced 40% [83•]. These reductions in biomass production may be indirectly caused by the decreased SOM, or they may also be the result of increased metal availability.

As SOM decreases following TD treatment, water retention decreases [85] and hydraulic conductivity increases [81]. This decrease in water availability inhibits both vegetative production and microbial activity. Further, the combustion of SOM may result in higher amounts of DOC [81] that can be leached out in saturated conditions. Thus, fewer resources are available for microorganisms associated with nutrient cycling, as evidenced by lower denitrification rates on TD-treated soils than those with added SOC [92]. At higher temperatures (above 500 °C), these effects may be exacerbated as the sharp declines in SOM are accompanied by mineralogical and textural shifts [85, 86••].

## Integrating Remediation and Restoration

The general effects of each remediation technique on soil function are summarized in Table 1. In all cases, the human activities causing contamination and the subsequent remediation alter soil function, although the magnitude and persistence of the alteration depend on site-specific conditions. Land managers may look for ways to mitigate these effects, as many of them are undesirable for soil restoration projects. Thus, research on these particular conditions will likely continue to gain prominence due to the shift to jointly considering remediation and restoration [16••, 17•].

This review identified some important variables to monitor with each method, and Table 2 lists some management practices that may mitigate some negative effects associated with each strategy. Given the variability in applying these remediation strategies, predicting the severity of alteration to soil function and the need for mitigation is difficult. Nonetheless, these tables are meant to be used in tandem by remediation practitioners to help recognize and address the impacts to soil function, which often go overlooked. A common trend among the different strategies is optimizing operational parameters for both the greatest contaminant reduction and the least negative impact to soil function. Since these parameters, such as dosage of compost, oxidant, or surfactant and heating temperature, are specific to each technique, filling this knowledge gap will take extensive research. Unfortunately, without that knowledge, making broad comparisons about effects on soil function between different methods may be inappropriate. Thus, one critical area for future research is the identification of threshold values for these operational parameters of each method, which may allow for meaningful comparisons between treatment methods.

These threshold values also maximize cost-efficiency, so they may gain more relevance for practitioners. For example, application of compost, chemical oxidants, or surfactants

**Table 1** Summary of impacts of site remediation techniques on four soil functions

| Remediation technique | Provide habitat and sustain biodiversity | Biomass production | Water storage and filtration | Nutrient cycling and waste management |
|---|---|---|---|---|
| In situ (general) | • Community shift favors contaminant degraders | • Reduced (or no) biomass production, based on effects of contaminant | • Hydrophobicity<br>• Danger of leaching/migration of contaminant | • Contaminant degrader species dominate resources |
| Ex situ (general) | • Fewer organic resources<br>• Reduced aeration and moisture | • Reduced root elongation and biomass | • Lower WHC<br>• Less infiltration | • Possible anaerobic conditions<br>• Fewer organic resources |
| Bioremediation | • Intermediate degradation products toxic to some species | • Genotoxicity persists beyond contaminant removal | • Altered pore networks<br>• Increased WHC | • Altered community structure |
| | • Contaminant degrader species dominate community | • More competition between plants and microorganisms | • Greater risk of leaching (e.g., DOC) | • High immobilization rate associated with high C:N |
| Phytoremediation | • Higher microbial biomass | • Dependent on contaminant concentration | • Improved aggregation and porosity | • Greater SOM degradation and more resource turnover |
| | • Increased microbial activity | | • Increased WHC and decreased leaching | |
| Chemical oxidation | • Inhospitable to pH-sensitive organisms<br>• Rapid recovery once oxidant is depleted | • Reduced germination and production for pH-sensitive species | • Decreased WHC<br>• Increased DOC<br>• Pores clogged by residual precipitates | • Decreased enzyme activities and microbial abundance |
| Electrokinetic | • Decreased microbial abundance | • Spatially variable germination and biomass growth | • Redistribution of solutes may impact leaching | • Spatially variable degradation and cycling |
| | • pH gradient inhospitable in some locations | •Higher bioavailability of heavy metals | • Danger of heavy metal migration | • Overall reduced microbial activity |
| Surfactant extraction | • Bacterial growth and activity inhibited<br>• Directly toxic to some species | • Increased toxicity to some species<br>• Adsorption to SOM reduces resource availability | • Textural shifts reduce WHC and increase $K_s$<br>• Permeability decreased | • Adsorption to SOM decreases degradation<br>• Altered community composition |
| Thermal desorption | • Initial decreases to microbial abundance<br>• Increased genotoxicity | • Increased availability of nutrients<br>• Possible genotoxicity | • Decreased WHC<br>• Increased $K_s$<br>• Increased leaching of DOC | • Decreased SOC reduces overall cycling<br>• Repopulation of microbes may decrease cycling |

*WHC* water holding capacity, *DOC* dissolved organic carbon, *C:N* carbon to nitrogen ratio, *SOM* soil organic matter, $K_s$ saturated hydraulic conductivity

**Table 2** Management considerations and practices that may mitigate impacts to soil function caused by each remediation technique

| Remediation technique | Management considerations for future restoration |
|---|---|
| In situ (general) | • Continuous monitoring to identify and address any migration |
| Ex situ (general) | • Proper care of stockpiles (e.g., stabilization, separation of topsoil and subsoil) |
| | • Replacement techniques to avoid compaction as much as possible |
| | • Incorporation of organic amendments throughout rooting zone |
| Bioremediation | • Appropriate compost/nutrient application rates to avoid nutrient loading or leaching |
| | • Identify species that may be tolerant of the resulting genotoxic compounds |
| | • Pair biological with surfactant, electrokinetic, and chemical oxidation to increase efficiency and reduce treatment times |
| Phytoremediation | • Ensure stabilization of contaminants with plant selection, buffer strips, and water monitoring |
| Chemical oxidation | • Appropriate dosage of oxidant to avoid persistence and reduce soil organic matter loss |
| | • Selecting appropriate oxidant for specific contaminants |
| | • Utilize chelator to regulate pH |
| | • Incorporate organic amendments |
| Electrokinetic | • Appropriate application of current to reduce spatial redistribution and direct toxicity |
| | • Spatially dependent nutrient application and organic amendments |
| Surfactant extraction | • Appropriate dosage of surfactant to avoid persistence and toxicity |
| | • Utilize bio (natural) surfactants to decrease risk of persistence |
| | • Limit separation due to mechanical agitation as much as possible |
| Thermal desorption | • Optimize heating time and temperature to reduce loss of soil organic matter |
| | • Mix in organic amendments (or topsoil) with treated soil |

enhances remediation, although excess dosages could result in damaging pH changes, loss of SOM, nutrient leaching, or increased toxicity without improving contaminant reduction any further. In electrokinetic and thermal treatment, the threshold value may be the point where excess current or heat degrades soil properties without further reducing contaminant concentration. Figure 1 shows a common relationship between contaminant reduction and operational parameters, wherein increasing dosage or temperature improves contaminant reduction. However, at some point (A), increasing resource input does not improve contaminant reduction. Thus, any additional dosage increases cost without any benefit; in fact, the increased dosage is likely to harm soil function. The dashed and dotted lines represent two possible trends in relative soil function associated with these conditions. The initial reduction of contaminants may be expected to improve soil function (point B), but eventually the increased exposure to the treatment (e.g., oxidant, surfactant, heat) will severely degrade those functions (point C). Thus, the most efficient project would utilize the dosage that maximized the sums of the two values.

This concept also highlights the importance of integrating remediation techniques, as using multiple tools can often increase efficiency. Some successful remediation projects utilize a pretreatment of chemical oxidation [93], surfactant extraction [48], or electrokinetic remediation [69]; once the

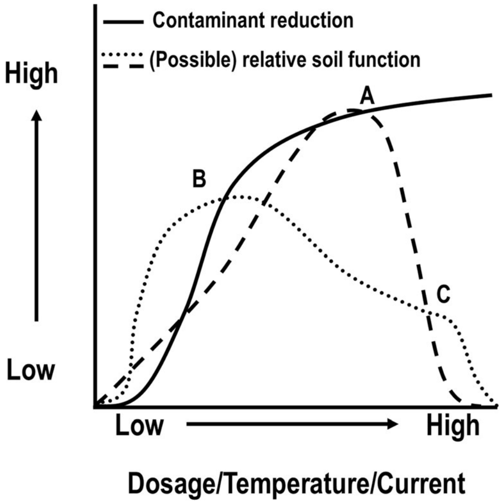

**Fig. 1** Conceptual figure demonstrating the increased contaminant reduction (*solid line*) resulting from increasing dosage of chemical, temperature of heating, or current in the electric field. Point A represents the threshold of contaminant reduction, beyond which increasing these parameters does not efficiently increase contaminant reduction. The *dashed line* represents one possible curve for relative soil function associated with these conditions. Soil function improves until contaminant reduction is maximized, and it greatly diminished with greater exposure. The *dotted line* represents another possible manifestation of relative soil function, wherein it is maximized at point B, prior to maximum contaminant reduction. Soil function decreases slowly until reaching a threshold of exposure (point C), beyond which function is greatly diminished

contaminant level is below a toxicity threshold, bioremediation is then employed. This practice can reduce cost of the more resource intensive practices and reduce time needed for bioremediation. This possibility of cost reduction is especially important at large-scale projects, as strategies like chemical oxidation or thermal treatment are often too expensive to be the sole means of remediation. Additionally, this integration utilizes soil function for remediation, rather than using it only as an indicator of restoration. Thus, it exemplifies the idea that reducing soil contamination and restoring soil function both should be considered, and can be attained, simultaneously.

## Conclusions

This review identified and summarized important impacts to soil properties resulting from soil remediation using some common technologies. Notably, nearly all of the technologies affected soil pH and SOM, which are important soil parameters that regulate many ecological processes. Nonetheless, these parameters by themselves are insufficient for describing changes to soil function caused by remediation techniques, as soil processes must be understood as complex, dynamic relationships between all soil properties. The magnitude of the effects on soil function is determined by type of application (e.g., in situ or ex situ) and treatment parameters (e.g., dosage of oxidant, temperature of TD). Future research should focus on identifying threshold values of these treatment parameters to allow for comparison of impacts to soil function between the different remediation strategies. Further, integrating several remediation strategies for a single project may offer a promising pathway for practitioners to pair contaminant reduction with restoring soil function.

### Compliance with Ethical Standards

**Conflict of Interest** The authors declare that they have no conflicts of interest.

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•• Of major importance

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