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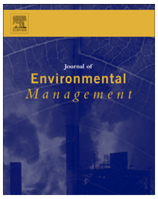

Review

Thermal remediation alters soil properties – a review

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ABSTRACT

Contaminated soils pose a risk to human and ecological health, and thermal remediation is an efficient and reliable way to reduce soil contaminant concentration in a range of situations. A primary benefit of thermal treatment is the speed at which remediation can occur, allowing the return of treated soils to a desired land use as quickly as possible. However, this treatment also alters many soil properties that affect the capacity of the soil to function. While extensive research addresses contaminant reduction, the range and magnitude of effects to soil properties have not been explored. Understanding the effects of thermal remediation on soil properties is vital to successful reclamation, as drastic effects may preclude certain post-treatment land uses. This review highlights thermal remediation studies that have quantified alterations to soil properties, and it supplements that information with laboratory heating studies to further elucidate the effects of thermal treatment of soil. Notably, both heating temperature and heating time affect i) soil organic matter; ii) soil texture and mineralogy; iii) soil pH; iv) plant available nutrients and heavy metals; v) soil biological communities; and iv) the ability of the soil to sustain vegetation. Broadly, increasing either temperature or time results in greater contaminant reduction efficiency, but it also causes more severe impacts to soil characteristics. Thus, project managers must balance the need for contaminant reduction with the deterioration of soil function for each specific remediation project.

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1. Introduction

Soil contamination by organic compounds affects thousands of sites across the United States, and many different land uses (USEPA, 2014). Organic contaminants can be directly toxic to biological organisms (Ramadass et al., 2015; Eom et al., 2007), so the functioning of both natural (Robson et al., 2004) and agricultural systems (Issoufi et al., 2006) can be altered. Additionally, this contamination may be a risk to human health (Ruby et al., 2016), which precludes residential or commercial use of these areas. Further, the contamination may migrate through air, soil, or water to affect a much broader area than the original contamination. Thus, remediation techniques may be required to quickly return the contaminated areas to previous land use and mitigate risk to human and ecosystem health.

Many types of methods for soil remediation are available (Lim et al., 2016; Khan et al., 2004), including biological, physicochemical, thermal, and integrated strategies, and the most appropriate method is a project-specific determination. While not applicable in all situations, thermal remediation offers greater control over operational parameters (e.g., heating time, temperature) and is used when goals include i) fast removal of contaminants; ii) strict adherence to a cleanup goal, requiring high reliability; and iii) reduction of long-term liability (Vidonish et al., 2016b). Thermal remediation is a category of techniques that use the application of heat to i) enhance the mobility of contaminants (e.g., steam/hot air injection); ii) separate contaminants from soil particles (e.g., thermal desorption, microwave heating); iii) transform contaminants into less toxic byproducts (e.g., pyrolysis); iv) destroy contaminants (e.g., incineration, smoldering); or v) immobilize contaminants (e.g., vitrification) (FRTR, 2017).

While thermal treatment can be faster and more reliable than some other methods, it typically requires more infrastructure and machinery, resulting in higher costs. Additionally, soil heating is known to affect numerous soil properties (Sierra et al., 2016; Yi et al., 2016; Pape et al., 2015), and the alteration of these properties may dictate land use following remediation. The extent of this alteration may be an important factor in the implementation of thermal remediation, as many practitioners are pairing remediation with subsequent reclamation or restoration efforts (Wagner et al., 2015). Thus, understanding the effects of thermal remediation on soil properties is critical information in the decision-making process that occurs at the beginning of a project. Extensive research has been conducted pertaining to the optimization of these techniques and the applicability across a range of situations (Gao et al., 2013; Thuan and Chang, 2012; Aresta et al., 2008). However, this research often ignores the impacts of thermal treatment on the remediated soil, so a comprehensive examination of the magnitude of the effects and their implications on soil function is needed (O'Brien et al., 2017a).

Connecting the effects of thermal remediation to soil function is vital in the subsequent reclamation or restoration process (Farag et al., 2015). Soil function, in this review, is understood as the ability of the soil to perform the following functions: i) serve as suitable habitat capable of sustaining biodiversity; ii) provide structure and a resource medium for biomass production; iii) store and filter water resources; iv) degrade, detoxify, and manage wastes through nutrient cycling and long-term resource storage; v) act as an engineering medium for human development; and vi) provide cultural and anthropological significance (Bone et al., 2010). The aims and circumstances of each project determine how the effects to soil function may be relevant in long-term project management (Ehrenfield, 2000). For example, some projects may be aimed at returning the land to commercial or industrial use, so potential productivity of the soil may be a low priority. However, soil strength and stability are essential when utilizing it as an engineering medium. Conversely, remediation projects on agricultural land or natural areas may have a goal of restoring the land to a pre-disturbance state, so reclamation goals may focus on the functions of providing habitat, biomass production, water management, and nutrient cycling.

Due to limited literature describing soil properties following thermal remediation, some wildfire research has been included in the review. Since the goal of thermal remediation is to create predictable, uniform heating, wildfire research conducted under field conditions is not applicable because it has widely variable heating conditions. Vegetation, litter depth, topography, soil water content, and soil pore networks are so variable across space and depth that heating time and intensity cannot be uniform within the soil profile (Busse et al., 2010; Archibold et al., 1998; Campbell et al., 1995). Only wildfire research that incorporated laboratory heating to simulate fire conditions may mimic conditions found in some remediation projects, so those studies are included in the review. Additionally, this review does not include any research that separates soil fractions that are less than <2 mm in diameter before heating, since soils are not typically separated at that scale prior to thermal remediation.

This review aims to examine the impacts of several thermal remediation techniques on soil properties and discuss the importance of those impacts in the context of contaminated site management. This assessment begins with a discussion of the principles of thermal remediation, and the most common thermal remediation heating times and temperatures are identified. Then, the direct impacts of thermal remediation to several individual soil characteristics are explored, with special emphasis on literature from remediation research projects. This information is supplemented by laboratory heating studies that elucidate the effects of heating on each property. Finally, the importance of these impacts in the implementation of remediation and reclamation strategies is discussed.

2. Thermal remediation for contaminant reduction

2.1. Pathways for thermal remediation

Thermal remediation can be applied to both surface- and subsoil materials to reduce a range of organic contaminants, including petroleum hydrocarbons (PHC), polycyclic aromatic hydrocarbons (PAH), polychlorinated biphenyls (PCB), and pesticides (Fig. 1a); additionally, thermal treatment is effective at reducing mercury concentration in soils. The four pathways for thermal remediation addressed in this review are i) enhanced mobility, ii) separation, iii) transformation, and iv) combustion (Vidonish et al., 2016b). A fifth pathway, immobilization, is possible through vitrification (Khan et al., 2004), but it is less common and forms a product that cannot be used as soil, so it is outside the scope of this review. Additionally, low temperature heating (<100 °C) can encourage increased biological degradation (Zeman et al., 2014), but it does not directly reduce contaminant concentration, so thermally enhanced biodegradation is also omitted from the review.

Enhanced mobility refers to using thermal treatment to increase the rate of removal of organic contaminants, typically in vapor phase. Methods that employ enhanced mobility, such as hot air injection or steam injection (Tzovolou et al., 2011; Schmidt et al., 2002), are typically applied in-situ, and they are akin to air sparging and soil vapor extraction (FRTR, 2017). This method recycles warm (up to 250 °C), non-contaminated air/steam through the contaminated zone in order to encourage vaporization, and it is typically limited to hydrocarbons with low Henry's constant values