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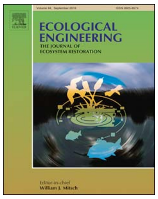

A large-scale soil-mixing process for reclamation of heavily disturbed soils

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ABSTRACT

Soil excavation associated with energy production or mineral extraction results in heavily disturbed landscapes that must be reclaimed to avoid long-term economic and environmental losses. A common practice in reclamation of these sites is topsoil replacement across the disturbed area. In some instances, this process requires importing topsoil from another location, known as topsoil transfer, which can be expensive and introduce a new seedbank, insect community, or plant pathogens. This research describes a soil-mixing process for disturbed soils that may be used to reduce costs associated with topsoil transfer and accelerate the recovery of soil function following a large excavation. This process was applied to two disturbed soils: i) crude-oil contaminated subsoil material; and ii) crude-oil contaminated subsoil material that was remediated using ex-situ thermal desorption. These soils were separately mixed with native, non-contaminated agricultural topsoil at 1:1 ratio (by volume). The native, disturbed, and mixed soils were characterized for soil physical, chemical, and biological properties, and statistics indicated that the mixtures were homogenous both spatially and with depth. However, the mixtures were significantly different from both the disturbed materials and native topsoil, primarily driven by changes in soil organic carbon, plant available nutrients, and biological activity. These results suggest that this mixing process can be used for soil reclamation at large-scale excavation sites to both reduce project costs and enhance recovery of soil parameters.

1. Introduction

Extraction of natural resources, including fossil fuels and other minerals, provides energy resources and raw materials crucial to modern society, as well as providing economic benefits. However, the processes of attaining these fuels can lead to heavily disturbed landscapes. Coal mining and quarrying, for example, often entail excavation of massive pits and stockpiling of soils for many years. This excavation destroys existing soil structure (Indorante et al., 1981), interrupts pore networks (Guebert and Gardner, 2001), decreases soil organic matter (SOM; Wick et al., 2009), and inhibits microorganisms (Miller et al., 1985). Stockpiling soil can also reduce SOM (Wick et al., 2009), alter nutrient cycling (Williamson and Johnson, 1990), and hinder vegetation reestablishment (Stahl et al., 2002), although many techniques have been developed to reduce the severity of those effects. Similarly, oil extraction requires reclamation of well pads, roads, and pipelines; further, accidental releases of crude oil can require remediation projects that may also disrupt soil function (O'Brien et al., 2017a). These remediation techniques, such as chemical oxidation, landfarming, or thermal desorption, also alter soil properties (Besalatpour et al., 2011; Villa et al., 2008), including pH, SOM, and microbial community dynamics. Accordingly, these projects can reduce topsoil production potentials (Boyer et al., 2011; Shrestha and Lal, 2011; Wick et al., 2009) by introducing subsurface material (e.g., mine tailings, remediated material) to the soil surface (Soon et al., 2000), which negatively affect soil function and require further management to reclaim or restore the land.

Several strategies are available to manage these disturbed sites. First, managers may choose not to take any restorative action and leave the mine spoils, deteriorated topsoil, or subsoil in place (Sena et al., 2014). This approach, natural attenuation, is the least costly, although it may not comply with regulations, and it may not be accepted by public opinion. This approach also takes a very long time compared to other approaches, but it can eventually restore soil function. Similarly,

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Abbreviations: MANOVA, multivariate analysis of variance; PCA, principal components analysis; SOC, soil organic carbon; SOM, soil organic matter; TD, ex-situ thermal desorption; TPH, total petroleum hydrocarbons

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soils can be remediated using a variety of techniques (O'Brien et al., 2017a) and then replaced. More commonly, topsoil is replaced across the disturbed area. Applying topsoil immediately improves soil function (Larney et al., 2012), although not always to pre-disturbance levels (Mummey et al., 2002). This topsoil may be stripped from the original site and stockpiled until reclamation, or it may be purchased and transferred from another location. Purchasing topsoil may be too expensive or unavailable in some instances, and it is accompanied by a risk of introducing a weed seedbank, an undesirable insect community, or plant pathogens. Further, caution must be used in selecting imported topsoil to avoid exposing the soil to trace elements or heavy metal loading. Additionally, transferring topsoil from another location simply creates a topsoil deficit elsewhere, effectively relocating the issue but not solving it. Finally, organic amendments, wastes, or composts may be incorporated into the disturbed material to increase SOM and improve biological communities (Stolt et al., 2001).

This research describes an approach that integrates these ideas, in which native topsoil is mixed into both contaminated and remediated disturbed soil materials. The disturbed material in this research was taken from a remediation site of a crude-oil pipeline leak that contaminated subsurface material down to 15 m below the surface. This study incorporates both the crude-oil contaminated material, as well as contaminated material that has been remediated using ex-situ thermal desorption. These two disturbed materials were separately mixed with local, non-contaminated agricultural topsoil. Given that the topsoil was locally available from the remediation project, the cost of purchasing and transporting the material was avoided, and the risk of introducing a seedbank of weeds or plant pathogens via local topsoil is low.

Several researchers have identified some benefits of mixing topsoil with disturbed material. By adding SOM-rich material, SOM of the overall mixture is increased, which is associated with improved biomass production and hydrologic function (Merino-Martin et al., 2017; Larney and Angers, 2011), as well as microorganism dehydrogenase activity (Smart et al., 2016). Topsoil mixing into the disturbed material also allows these benefits to extend deeper in the profile, which is vital for successful reclamation (Chenot et al., 2017; Larney et al., 2012). Thus, using topsoil as a mixing agent both aids in recovery of soil function (O'Brien et al., 2017b; Callaham et al., 2002; Roh et al., 2000) and also reduces the amount of topsoil needed for replacement, which may be vital in projects with topsoil deficits (Merino-Martin et al., 2017; Carson et al., 2014). To date, these benefits of topsoil mixing have been primarily identified at the laboratory and greenhouse level. Thus, this research is valuable in helping to identify a process by which these benefits can be attained that is i) applicable at a large scale and ii) results in uniform soil mixing.

The aim of this research was to assess the homogeneity of research plots constructed using a large-scale mixing technique applied near an active soil remediation project. This determination was made by analyzing soil characteristics of the soil mixtures and comparing them to unmixed samples at four different depths. Multivariate analyses were employed to compare both homogeneity within each treatment and differences between the treatments. Identifying homogeneity within the plots indicates that the added topsoil was spread evenly throughout, which maximizes the benefits of mixing. Additionally, this work provides a framework for separating treatment effects of soil mixing from the natural variability of soil properties. This study provides vital information on understanding the effects of excavation and reclamation on soil parameters, as well as identifies soil-mixing as a viable alternative to current practices.

2. Materials and methods

2.1. Study area and soil materials

This research took place adjacent to an active remediation site in Mountrail County, ND, USA (48°31′35.4″N, 102°51′25.72″W). The site is currently using thermal desorption to treat a pipeline spill that released Bakken crude oil into an agricultural field and underlying subsoil. Research plots were constructed near the site using three different soils to create five treatments. Non-contaminated, native topsoil acted as a control (A; Treatment 1). The A is mapped as Williams-Zahl loams (Williams: fine-loamy, mixed, superactive, frigid Typic Argiustolls; Zahl: fine-loamy, mixed, superactive, frigid Typic Calciustolls) (NRCS, 2015). It was excavated and stockpiled for several months prior to plot construction during the course of the remediation project. Topsoil stockpiles were each approximately 9 m tall, (90 m long by 30 m wide at the highest point), with 2H:1 V slopes, and they were not seeded. Thus, the A used in the plots was the original soil, and it received no additional treatment other than the excavation and replacement. Crude oil-contaminated subsurface soil material was taken from the stockpile of untreated material in the remediation project (SP; Treatment 2). The SP is a mixture of soils taken across the entire width and depth of the site, and was initially passed through a 10 cm screener (R155 Screener, McCloskey International, Keene, Ontario) to ensure a uniform material. The SP was treated by an RS 40 Thermal Desorption/Oxidation unit at 350 °C for 10 min to create thermal desorption-treated subsurface material (TD; Treatment 3). Both SP and TD materials were originally excavated on-site, but they were a mixture of contaminated material from down to 15 m below ground surface; thus, the original depth of these materials is not identified. Although neither SP nor TD material originated from the zone of soil genesis, for ease of reference, these materials will be referred to hereafter as "SP soil" and "TD soil". The final two treatments were mixtures created using the A, TD, and SP soils: 1:1 mixture (by volume) of A and SP (SPA; Treatment 4) and 1:1 mixture (by volume) of A and TD (TDA; Treatment 5).

2.2. Mixing process and plot construction

The soil mixtures, SPA and TDA, were created by the following process. Piles of each soil type (A, SP, and TD) were staged adjacent to the plot area for construction. Two material types were added into a screener in alternating 0.6 m^3 excavator bucket-loads (336E Hydraulic excavator, Caterpillar Inc., Peoria, Illinois). For example, one bucket of A was placed into the hopper for the screener, followed by one bucket of TD (or SP), followed by one bucket of A, and so forth (Fig. 1a). After passing through the initial screener, the mixed soil passed through a second screener and moved via material stacker (ST80 Wheeled stacker, McCloskey International) approximately 4.5 m into the air before being deposited into a staging pile of mixed soil (Fig. 1b).

Thirty plots were constructed, with each treatment repeated twice in each of three replications. Each plot holds approximately 230 m^3 of soil (17 m × 15 m × 0.9 m). The soil was loaded from the staging piles into dump trucks (730 Ejector articulated dump truck, Caterpillar Inc.) that hauled the soil into each plot and dumped the material freely onto the prepared area (Fig. 1b and c). Each plot required 25 truckloads of soil, and they were constructed in sequence such that the dump trucks did not drive over any completed plots. Once the material was deposited in each plot, it was spread using a tracked vehicle with an excavator bucket (336E Hydraulic excavator, Caterpillar, Inc.) to make the plots as even as possible (Fig. 1d).

2.3. Sampling procedure and analyses

Plot construction was completed in November 2015 (Fig. 2), and core sampling occurred in early December 2015. The plots were sampled as soon as possible after construction to ensure that measurements reflected the conditions of each plot due to mixing and did not include any natural recovery of soil characteristics. All soil sampling was done in a nested 12 m × 12 m square to avoid border areas that may be subject to mixing between treatments. A Giddings soil probe (Giddings Machine Company, Inc., Windsor, Colorado) was used to take four cores to 0.9 m depth from each plot. The cores were taken at three points