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Implications of Using Thermal Desorption to Remediate Contaminated Agricultural Soil: Physical Characteristics and Hydraulic Processes

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Abstract

Given the recent increase in crude oil production in regions with predominantly agricultural economies, the determination of methods that remediate oil contamination and allow for the land to return to crop production is increasingly relevant. Ex situ thermal desorption (TD) is a technique used to remediate crude oil pollution that allows for reuse of treated soil, but the properties of that treated soil are unknown. The objectives of this research were to characterize TD-treated soil and to describe implications in using TD to remediate agricultural soil. Native, noncontaminated topsoil and subsoil adjacent to an active remediation site were separately subjected to TD treatment at 350°C. Soil physical characteristics and hydraulic processes associated with agricultural productivity were assessed in the TD-treated samples and compared with untreated samples. Soil organic carbon decreased more than 25% in both the TD-treated topsoil and the subsoil, and total aggregation decreased by 20% in the topsoil but was unaffected in the subsoil. The alteration in these physical characteristics explains a 400% increase in saturated hydraulic conductivity in treated samples as well as a decrease in water retention at both field capacity and permanent wilting point. The changes in soil properties identified in this study suggest that TD-treated soils may still be suitable for sustaining vegetation, although likely at a slightly diminished capacity when directly compared with untreated soils.

Core Ideas

- Soil from a crude oil spill site was remediated using thermal desorption.
- Thermal desorption treatment reduced SOC, SSA, and aggregation.
- Changes to physical properties caused increased K_s and decreased water retention.
- Soils subjected to TD may be less effective in crop production than native soil.
- Adding organic amendments to TD-treated soil may ameliorate some effects of TD.

Crude oil and natural gas production within the Bakken and Three Forks shale formations has increased dramatically in the last decade and now contributes billions of dollars annually to economies in the northern Great Plains and southern Canada. However, accidental releases of petroleum products associated with this process can occur. In this region, which has been historically comprised of predominantly agriculture-based economies, these products are likely to be released in cropland and rangelands. These releases may be devastating environmentally and economically because the petroleum hydrocarbons (PHCs) from the oil can be directly toxic to vegetation, reduce plant germination and growth (Liste and Prutz, 2006; Kisic et al., 2009), change hydrology (de Jong, 1980; Roy and McGill, 1998), and inhibit biological activity in the soil (Dorn et al., 1998; Eom et al., 2007). These effects must be alleviated before the land can be returned to agricultural use. Thus, remediation methods in agronomic systems should not only be judged by the length of cleanup time and the ability to reduce PHC concentrations, but they must also demonstrate that remediated soil is capable of sustaining vegetation.

Ex situ thermal desorption (TD) (Fig. 1) is a remediation technique that can reliably meet cleanup standards in a shorter timeframe than many other strategies (Khan et al., 2004). The use of TD is effective in the removal of PHC contamination from a variety of causes, including coking plants (Biache et al., 2008), diesel fuel (Falciglia et al., 2011), and industrial waste (Norris et al., 1999). The TD process involves the excavation and thermal treatment of contaminated materials in a desorption unit that enhances contaminant vaporization (Lighty et al., 1990; USEPA, 1994). The vaporized contaminants are passed through a thermal oxidation combustion chamber and released into the atmosphere, and the treated soil is available for reuse.

Because most studies involving TD assess only contaminant removal (Falciglia et al., 2011; Tatano et al., 2013; Qi et al., 2014; McAlexander et al., 2015) and omit characterizing the soil, little information about the properties of TD-treated soil exists. In the few studies that did assess some soil physical properties, TD altered particle size distribution (Bonnard et al., 2010) and

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Abbreviations: DOC, dissolved organic carbon; EGME, ethylene glycol monoethyl ether; PAW, plant-available water; PHC, petroleum hydrocarbon; SOC, soil organic carbon; SOM, soil organic matter; SS, subsoil; SSA, specific surface area; SS-TD, subsoil treated by thermal desorption; TD, ex situ thermal desorption; TS, topsoil; TS-TD, topsoil treated by thermal desorption.

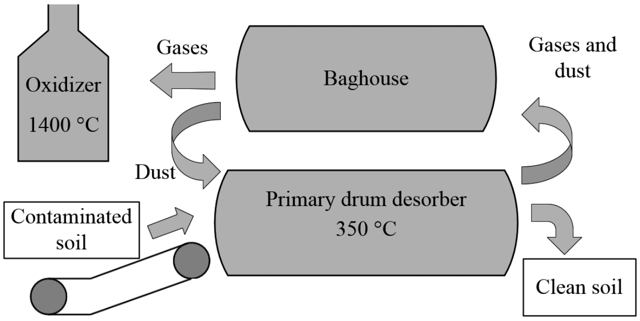

Fig. 1. Schematic of the thermal desorption process.

reduced soil organic matter (SOM) (Tatano et al., 2013; Sierra et al., 2016). Additionally, TD-treated soils used in greenhouse studies resulted in reduced plant growth (Dazy et al., 2009) and decreased activity in microorganisms (Cebron et al., 2011). Soil–water relationships in TD-treated soil have not yet been described in the literature.

An additional, although not primary, function of TD is the creation of biochar when oxygen-limiting conditions occur within the primary drum desorber (Tucker and Platts, personal communication, 2013). In some cases, biochar applications have been shown to increase surface area (Laird et al., 2010), soil organic carbon (SOC) (Sun et al., 2013), and water retention (Streubel et al., 2011; Ulyett et al., 2014). However, the quantification and characterization of biochar created from pyrolysis of SOM during the TD process has not been studied. Additionally, variability in the literature regarding the characteristics and effects on soil processes of biochar amendment demonstrates the uncertainty regarding effects of any biochar created during the TD process (Atkinson et al., 2010; Jeffery et al., 2011).

Although no opportunity exists to describe field-scale plant response in TD-treated soils, assessing some physical and hydraulic properties of TD-treated soils may indicate their potential for crop production. Increases in SOC (Monreal et al., 1997; Arvidsson, 1998) and aggregate stability (Barzegar et al., 2002) are both associated with higher crop yields. Additionally, crop production has been directly correlated with soil water retention (Martin et al., 2005), and numerous studies associate crop yields with hydraulic characteristics (O'Leary and Connor, 1997; Fernandez-Ugalde et al., 2009; Keller et al., 2012).

The purpose of this study was to evaluate how TD treatment affects the capacity of an agricultural soil to sustain vegetation. This evaluation was based on the examination of soil physical and hydraulic properties that have been associated with cropland and rangeland production. The results of this study may highlight benefits and drawbacks of using TD after contamination of agricultural soil and therefore influence future remediation projects.

Materials and Methods

Soil Sampling

The soil samples were taken near an active remediation site in Mountrail County, North Dakota (48°31′35.4″N, 102°51′25.72″W) that had been contaminated with Bakken crude oil as a result of a pipeline leak. The native, noncontaminated topsoil and subsoil used in this study were collected immediately outside the boundary of the remediation site. The soils are mapped as Williams-Zahl loams (Williams: Fine-loamy, mixed, superactive, frigid Typic Argiustoll; Zahl: Fine-loamy, mixed, superactive, frigid Typic Calciustoll), which have a productivity index of 76 and are considered "farmland of statewide importance" (USDA–NRCS, 2015).

Soil Preparation

Native, noncontaminated topsoil (TS) and subsoil (SS) were treated separately (2.9 Mg each) by a RS40 thermal desorption/oxidation unit (Nelson Environmental Ltd.) at 350°C for 15 min to generate TD-treated topsoil (TS-TD) and TD-treated subsoil (SS-TD). The four samples were air-dried, ground to pass through a 2-mm sieve, and stored at 20°C in plastic containers. Subsamples used for aggregate stability testing were ground to pass through an 8-mm sieve.

Physical Characteristics

Particle size analysis was conducted using the hydrometer method (Gee and Or, 2002; ASTM, 2007). Mineralogical analysis was performed using X-ray diffraction for quantitative analysis at a private laboratory (Activation Laboratories Ltd.). Total carbon and soil inorganic carbon were evaluated using a Primacs TOC Analyzer (Skalar Analytical B.V.); SOC was determined as the difference between total carbon and inorganic carbon.

Specific surface area (SSA) was calculated using the ethylene glycol monoethyl ether (EGME) retention method (Pennell, 2002). After the application of 2 mL of EGME to 1 g of oven-dry soil, samples were placed in a vacuum desiccator with anhydrous $CaCl_2$ and evacuated for 1 h. After 24 h, the samples were removed and weighed twice per day. The desiccator was evacuated after each weighing. When the weight of each sample was constant within ±2.5%, SSA was calculated using the EGME conversion factor (Pennell, 2002).

Aggregate stability and size distribution were calculated using the wet sieving method described by Six et al. (1998). Water-stable aggregates were separated by wet sieving into three fractions: (i) microaggregates (between 53 and 250 μm), (ii) small macroaggregates (between 250 and 2000 μm), and (iii) large macroaggregates (between 2000 and 8000 μm). Aggregate samples were corrected for sand content according to Denef et al. (2001). Total aggregation was determined from the sum of micro-, small macro-, and large macroaggregates. Four replications were completed for each of the physical parameters assessed.

Hydraulic Characteristics

The water drop penetration time test was performed on 50 g of air-dried soil. Samples were placed in a Petri dish and manually smoothed, and six 50-μL drops of deionized water were placed systematically on the soil surface from a height of 1 cm (Hallin et al., 2013). The time for the drop to completely infiltrate the soil surface was recorded.

Saturated hydraulic conductivity (K_s) was determined using a constant head method with Tempe pressure cells (adapted from Reynolds and Eldrick, 2002). Samples were placed into brass rings and tapped with a wooden dowel approximately 50 times to achieve bulk densities within ±2.5% of one another. Samples were packed into Tempe cells and saturated from the bottom up with deaerated 0.01 mol L^{-1} CaCl solution for 72 h. Once fully saturated, the liquid supply was attached to the top of each Tempe cell. Liquid passing through each cell was collected in beakers and measured every 30 min for at least 2 h. Darcy's law was used to calculate K_s (Reynolds and Eldrick, 2002). Leachate accumulated from the first 30 min of saturation from each cell was tested for dissolved organic carbon (DOC) using combustion catalytic oxidation with a TOC-V_{CPH} Analyzer (Shimadzu Corp.).

Plant-available water (PAW) and water retention values were determined using pressure plate extractors (Soilmoisture Equipment Corp.) calibrated to five different pressures (10, 33, 100, 500, and 1500 kPa). Rubber rings, 1 cm in height and 5.5 cm in diameter, holding approximately 25 g of soil were wetted with reverse-osmosis filtered water, placed on the pressure plates, and allowed to saturate for 4 h. Once saturated, each pressure was applied for 72 h, after which the gravimetric water content was determined. Plant-available water was calculated by subtracting the volumetric water content at 1500 kPa from the volumetric water content at 33 kPa. Four replications were performed for each hydraulic characteristic assessed.

Statistical Analysis

Results from the physical and hydraulic tests were analyzed using one-way ANOVA with mean difference significance at the $\alpha = 0.05$ level. Pairwise comparisons of all four samples were conducted with a post-hoc Tukey HSD test. All statistical tests were performed with R 3.2.1 software using the "stats" (R Core Team, 2014) and "multcomp" (Hothorn et al., 2008) packages.

Results and Discussion

Particle size distribution was not significantly affected by TD treatment; however, TD treatment in this study tended to cause a slight increase in sand-sized particles and a slight decrease in clay-sized particles in both the TS-TD and SS-TD (Table 1). These trends in particle size distribution were in accordance with other studies using TD, even those heated up to 500°C (Bonnard et al., 2010) and 650°C (Ouvrard et al., 2011), which were temperatures substantially higher than achieved in this study. Similar decreases in clay-sized particles and increases in sand-sized particles as those in this study have been found in laboratory heating studies between 170 and 460°C (Giovannini et al., 1988). Dramatic textural shifts can occur after heating at much higher temperatures (Zihms et al., 2013; Pape et al., 2015) because temperature thresholds at which clay minerals begin to deteriorate are normally above 500°C (Tan et al., 1986). For example, the structure of bentonite, often composed of smectite minerals, does not deteriorate due to heating until temperatures reach over 700°C; kaolinite structure begins to degrade at 530°C (Tan et al., 1986). In this study, mineralogical analysis of TD-treated samples indicates that deterioration of clay minerals did not occur (Table 2); as a result, the texture was not significantly changed. Nonetheless, the slight decrease in clay-sized particles was the primary driver for a substantial reduction in SSA in this study because clay-sized particles generally dictate SSA (Petersen et al., 1996). After TD treatment, SSA decreased by 20% in the TS-TD and 15% in the SS-TD samples (Table 1).

The response of SOC shows a similar trend to SSA; TD treatment caused a 30% reduction in SOC in the TS-TD and a 25% reduction in the SS-TD unit relative to untreated soil (Fig. 2). This loss is roughly the same magnitude of other TD studies (Bonnard et al., 2010; Huang et al., 2011; Ouvrard et al., 2011) and is expected when soils are heated to 350°C (Varela et al., 2010; Kiersch et al., 2012), although that loss may be dependent on heating time. For example, shorter exposure to heating at 350°C (i.e., 10 min) could reduce the loss of SOC to approximately 12% (Thomaz and Fachin, 2014). Conversely, lengthening the heating time up to an hour could result in almost complete removal of SOC (Terefe et al., 2008; Zavala et al., 2010; Sierra et al., 2016). A major concern from an agronomic viewpoint is the mobility of the remaining SOC. After just 30 min of water flow under saturated conditions, the TS-TD horizon lost almost 0.1% of the DOC (Fig. 3). Loss of DOC via leaching may have widespread implications on nutrient cycling and transport (Bolan et al., 2011); consequently, stabilizing the SOC should be a concern when considering the use of these soils for agricultural production.

Table 1. Particle size distribution, specific surface area, and water drop penetration test time of untreated topsoil and subsoil and thermal desorption–treated topsoil and subsoil.

	Soil†			
	TS	TS-TD	SS	SS-TD
	Particle size distribution (% by weight)			
Sand	47.3 ± 0.6‡	49.4 ± 1.4	48.0 ± 0.1	49.0 ± 1.0
Silt	33.5 ± 0.8‡	31.9 ± 1.1	31.4 ± 0.8	32.2 ± 1.5
Clay	19.2 ± 0.8‡	18.8 ± 0.3	20.6 ± 0.7	18.8 ± 1.2
	Specific surface area (m^2 g^{-1})			
	89.6 ± 2.3ab§	71.2 ± 4.3c	93.3 ± 3.4a	80.0 ± 4.2bc
	Water drop penetration test (s)			
	<1‡	1.16 ± 0.2	<1	1.16 ± 0.2

† TS, topsoil; TS-TD, thermal desorption–treated topsoil; SS, subsoil; SS-TD, thermal desorption–treated subsoil.

‡ No significant differences at $\alpha = 0.05$ within the row.

§ Different letters within rows indicate significance at $\alpha = 0.05$ (Tukey's HSD test).

Table 2. Mineralogical analysis and distribution of clay fraction of untreated topsoil and subsoil and thermal desorption–treated topsoil and subsoil.

	Soil†			
	TS	TS-TD	SS	SS-TD
Mineral (% by weight)				
Quartz	48.2	42.3	38.6	40.9
Plagioclase	17.4	16.8	13.9	13.6
Microcline	6.7	3.3	5.2	4.8
Muscovite/illite	6.2	6	5.6	6.9
Kaolinite	0.6	0.7	0.7	trace
Amphibole	trace	trace	0.7	trace
Dolomite	2.1	2.9	4	2.5
Calcite	trace	0.4	1	1.1
Amorphous	18.9	27.5	30.2	30.1
Clay fraction (% by weight)				
Smectite	42	42	57	51
Illite	46	47	33	37
Kaolinite	8	8	7	9
Chlorite	4	3	3	3

† TS, topsoil; TS-TD, thermal desorption–treated topsoil; SS, subsoil; SS-TD, thermal desorption–treated subsoil.

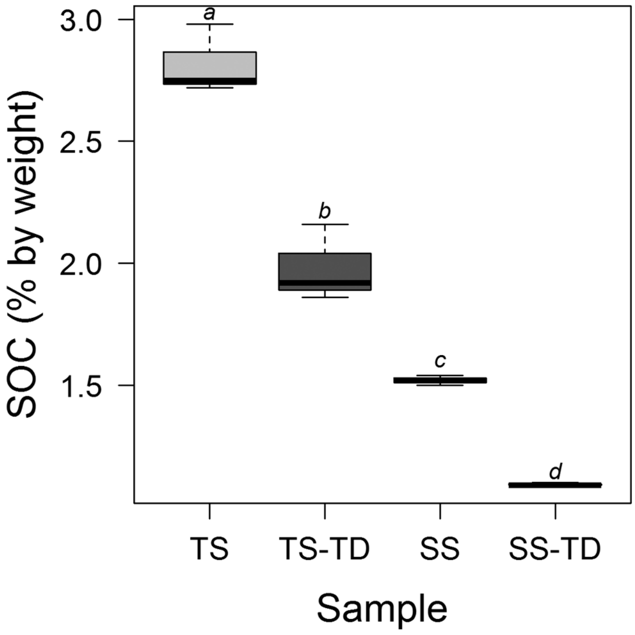

Fig. 2. Boxplot of soil organic carbon (SOC) of untreated topsoil (TS) and subsoil (SS) and thermal desorption (TD)-treated topsoil (TS-TD) and subsoil (SS-TD). Different letters indicate significance at $\alpha = 0.05$ (Tukey's HSD test).

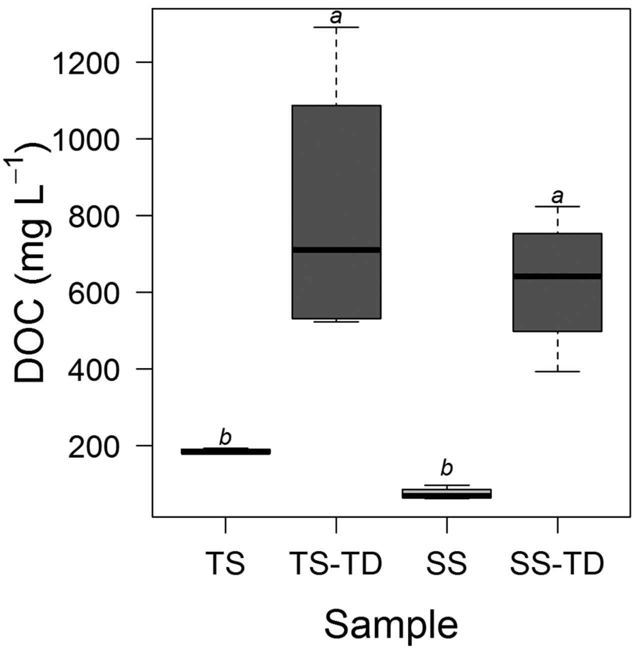

Fig. 3. Boxplot of dissolved organic carbon (DOC) leachate taken from first 30 min of saturated hydraulic conductivity test of untreated topsoil (TS) and subsoil (SS) and thermal desorption (TD)-treated topsoil (TS-TD) and subsoil (SS-TD). Different letters indicate significance at $\alpha = 0.05$ (Tukey's HSD test).

The loss of SOC after TD treatment is likely linked to the reduction in total aggregation (Table 3); many studies have noted the correlation between SOM or SOC and aggregate stability (Chaney and Swift, 1984; Jastrow, 1996; Six et al., 1998). However, these dynamics are complex during soil heating events (Mataix-Solera et al., 2011). Soils heated at lower temperatures (170–220°C) may contain more water-stable aggregates, likely due to hydrophobicity induced by heating (Garcia-Corona et al., 2004). Similarly, heating at much higher temperatures (750–1000°C) can result in the reaggregation of degraded minerals that may also exhibit greater aggregate stability (Campo et al., 2014). In this study, total aggregation was reduced by 20% in the TS-TD, which agrees with studies that describe a decrease in aggregate stability at temperatures between 350 and 400°C (Varela et al., 2010; Zavala et al., 2010). Water-stable aggregation did not decrease in the SS-TD, which agreed with other research that has found aggregate stability is not affected by loss of SOC associated with heating (Giovannini et al., 1988).

Although both of these responses have justification in the literature, differences in aggregation in the TS and SS are notable. Nearly every other metric assessed in this study found no difference between the TS-TD and SS-TD. Total aggregation may be an exception because it is closely related to SOC, which was significantly different between the untreated TS and SS. The clay mineralogy may also be contributing to this behavior; the higher SSA associated with the greater proportion of smectite in the SS may be more resistant to disaggregation.

These changes in aggregation may affect hydraulic properties, such as infiltration. Increasing soil aggregation increases cumulative infiltration rates (Martens and Frankenberger, 1992), and infiltration rates decrease as the proportion of small aggregates increases (Loch and Foley, 1994). These decreases may be associated with an increased rate of surface seal deposition from the breakdown of smaller, weaker aggregates (Fox and Le Bissonnais, 1998). Thus, the combination of decreased SOC and a reduction in total aggregation may make TD-treated soils especially susceptible to low infiltration rates and subsequent erosion (Lado et al., 2004). However, this occurrence may only be documented once the soils have been replaced and exposed to field conditions.

Similarly, initial infiltration rates could be inhibited by hydrophobicity that has been associated with soil heating (Garcia-Corona et al., 2004; Varela et al., 2010). However, the water drop penetration test (Table 1) indicated that hydrophobicity is not evident after

Table 3. Proportion of water-stable aggregates within each size distribution.

Soil†	Size distribution‡			
	LM	SM	m	Total aggregation
	g sand free aggregate g^{-1} soil			
TS	0.05 ± 0.007a§	0.18 ± 0.004a	0.27 ± 0.013a	0.50 ± 0.012a
TS-TD	0.05 ± 0.008a	0.15 ± 0.006b	0.21 ± 0.007b	0.41 ± 0.010b
SS	0.01 ± 0.006b	0.12 ± 0.008c	0.29 ± 0.005a	0.41 ± 0.004b
SS-TD	0.04 ± 0.004a	0.11 ± 0.003c	0.24 ± 0.006b	0.39 ± 0.008b

† TS, topsoil; TS-TD, thermal desorption–treated topsoil; SS, subsoil; SS-TD, thermal desorption–treated subsoil.

‡ LM, 2000–8000 μm; SM, 250–2000 μm; m, 53–250 μm; total aggregation, 53–8000 μm.

§ Different letters within columns indicate significance at $\alpha = 0.05$ (Tukey's HSD test).

TD treatment, likely because the soils in this study were heated to 350°C. Heat-induced hydrophobicity is generally highest when soils are heated between 175 and 200°C (DeBano, 2000), but it decreases as heating temperature increases due to the loss of organic compounds (DeBano et al., 1976; Doerr et al., 2005).

In addition to influencing infiltration and erosion, texture, aggregation, and SOC influence water movement within the soil (Olness and Archer, 2005; Dexter et al., 2008; Resurreccion et al., 2011; Arthur et al., 2013). Two good indicators of water movement are K_s and water retention. Relating to a texture gradient, K_s has an inverse relationship with the presence of clay sized particles, whereas water retention has a positive relationship (Saxton and Rawls, 2006; Pachepsky and Park, 2015). Although the texture of TD-treated soils did not change significantly, the changes in K_s and water retention were more dramatic. Both the TS-TD and SS-TD K_s values were above 2.0 cm h^{-1}, which is a 400% increase from the TS and SS (Fig. 4). Also, this K_s value of 2.0 cm h^{-1} is more characteristic of a sandy loam than a loam (Rawls et al., 1982). Similarly, the gravimetric water content at field capacity (33 kPa) and wilting point (1500 kPa) of the TD-treated samples were 19 and 9%, respectively (Table 4), which were more comparable with a sandy loam rather than a loam (Saxton and Rawls, 2006). Thus, some of the hydraulic characteristics of the TD-treated soils seem to belie the properties normally associated with its texture.

Looking beyond texture, these discrepancies may also be explained by the interaction of SOC and aggregation. Decreases in SOC and aggregation can reduce water retention (Rawls et al., 2003) and PAW (Olness and Archer, 2005). Interestingly, PAW did not follow the trends shown in the K_s and water retention. Although gravimetric water content decreased with increasing pressure (Table 4), the rate of decrease was similar between untreated and TD-treated samples. Therefore, PAW remained relatively constant after TD treatment, and the values were all fairly representative of other loams (Cassel and Sweeney, 1974). Although this study did not attempt to quantify the biochar created during the TD process, some form was likely present. Regardless, the type and amount created was not sufficient to keep physical and hydraulic parameters consistent with untreated soil.

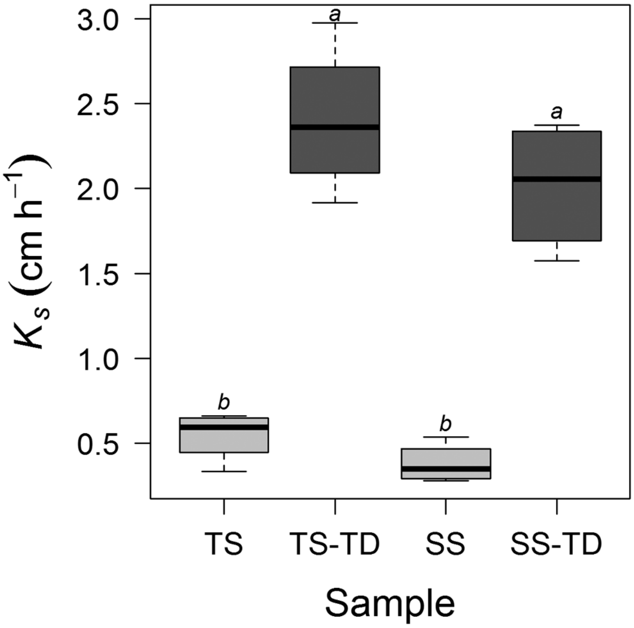

Fig. 4. Boxplot of saturated hydraulic conductivity (K_s) of untreated topsoil (TS) and subsoil (SS) and thermal desorption (TD)-treated topsoil (TS-TD) and subsoil (SS-TD). Different letters indicate significance at $\alpha = 0.05$ (Tukey's HSD test).

The information obtained from these physical and hydraulic parameters can begin to answer two vital questions about using TD-treated soils to remediate soil in agricultural regions. First, will agricultural productivity of a certain soil change after TD treatment? The results of this study suggest that a decrease in yield is possible when comparing TD-treated soils with pretreated levels. Although texture was not significantly altered by TD treatment, the K_s and water retention of TD-treated samples responded as though the distribution of sand-sized particles had increased substantially. This behavior may indicate reduced yield potential because soils with more sand-sized particles have been associated with lower yields than soil with more fine particles (Simpson and Siddique, 1994; Nyiraneza et al., 2012), mostly due to soil–water relationships. Further, the loss of SOC, accompanied by decreased aggregation in the TD-treated soils, could result in increased compaction (Baumgartl and Horn, 1991) and associated reduced yields (Oussible and Larson, 1992; Gregorich et al., 2011). This loss of SOC could be exacerbated through additional leaching due to an increase in K_s.

The second question this study can address is much broader: can TD-treated soil be used for agricultural production? Although direct comparison between pretreatment and post-treatment soils indicates that TD treatment alters some soil characteristics, the extent of these alterations does not appear significant enough to prevent use for crop production. Even though the TD-treated soil

Table 4. Gravimetric soil water content with standard error at various pressures for untreated topsoil and subsoil and thermal desorption–treated topsoil and subsoil.

Soil†	Soil moisture pressure (kPa)					Plant-available water
	10	33	100	500	1500	
	Gravimetric water content					
	% by weight					cm^3 cm^{-3}
TS	26.1 ± 1.19‡	22.9 ± 0.35a§	20.1 ± 0.3a	13.2 ± 0.03a	12.2 ± 0.03a	11.3 ± 0.37†
TS-TD	23.3 ± 1.07	18.6 ± 0.2b	16.1 ± 0.15b	10.7 ± 0.22c	8.94 ± 0.05c	10.1 ± 0.25
SS	25.7 ± 1.3	21.6 ± 0.37a	19.7 ± 0.2a	12.2 ± 0.13b	10.6 ± 0.1b	11.5 ± 0.41
SS-TD	22.8 ± 0.57	19.7 ± 0.4b	16.0 ± 0.36b	10.8 ± 0.14c	8.74 ± 0.06c	11.5 ± 0.46

† TS, topsoil; TS-TD, thermal desorption–treated topsoil; SS, subsoil; SS-TD, thermal desorption–treated subsoil.

‡ No significant differences at $\alpha = 0.05$ within the column.

§ Different letters within columns indicate significance at $\alpha = 0.05$ (Tukey's HSD test).

behaves more like a sandy loam than its measured texture, sandy loams are routinely used in crop systems. Additionally, the characteristics identified to change with TD treatment could all be modified with soil amendments; applying organic amendments would increase the SOC and likely increase aggregation and water retention, as well as slow DOC leaching by reducing K_s.

Conclusions

These laboratory assessments of TD-treated soils suggest that water balances, dictated by SSA, SOC, and aggregation, are the primary area of concern when considering using TD for remediation in agricultural systems. The changes to these physical and hydraulic properties revealed in this study indicate that returning TD-treated soil to pretreatment levels of productivity may require additional management, likely soil amendments such as manure or compost. Additionally, to more fully answer these questions about the suitability of TD-treated soils for use as topsoil in agricultural systems, the effects of TD treatment on soil chemical and biological parameters should also be investigated. A notable distinction to this study is that it used noncontaminated samples. Incorporating varying levels of pollutants, especially crude oil, into the soil before TD treatment may have distinctly different effects on the characteristics studied here. However, this study offers valuable baseline knowledge regarding what the TD process does to noncontaminated soils so that comparisons may be made in the future using contaminated soils.

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