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Impacts of thermal and smouldering remediation on plant growth and soil ecology

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ABSTRACT

Thermal (<1000 °C) and smouldering (600–1100 °C) remediation strategies potentially remove significant quantities of persistent organic pollutants from contaminated sites, reducing environmental and public health impacts while improving suitability for subsequent land use. However, high temperatures change the chemical and biological quality of soils, thus making restoration more difficult and costly. Here, we quantified the effects of soil heating (ambient to 1000 °C) and smouldering remediation (>1000 °C), which involved flameless combustion of hydrocarbon laden soils, on two topsoil types. The experimental aim was to determine the thermal-related effects on soil ecology, including geochemical properties, microbial activity, and plant growth.

There was a negative trend in plant growth with treatment temperature with red clover (*Trifolium pratense*) and red fescue (*Festuca rubra*). This appears to be related to geochemical changes in the soil, particularly atmospheric losses of nitrogen and reduced nutrient availability (e.g., Cu, Zn, and P). Consequently the ability of soils to immediately recover with active microbial communities rapidly declined when heated ≥500 °C. Microcosm experiments, such as these, inform engineers and land-use managers of chemical and biological impacts, and provide guidance as to the nutritional and biological requirements for effective land restoration and rehabilitation.

1. Introduction

Soil contamination remains a global problem. Europe faces an estimated 342,000 sites of known contamination and a further 2.5 million potentially contaminated sites (Van Liedekerke et al., 2014). A great deal of effort has gone into developing remediation processes to remove or reduce the impact of these contaminants in the environment. For organic pollutants such as oils, tars, and polycyclic aromatic hydrocarbons (PAHs), a range of techniques has been developed using heat treatment or combustion processes to volatilise and extract, or destroy, these contaminants. Typical operating ranges vary from 100 °C for many vapour extraction methodologies (Heron et al., 2005; Buettner and Daily, 1995), to in excess of 1000 °C during ex-situ incineration of heavy oils and tars (Anthony and Wang, 2006). Smouldering remediation exposes soils to temperatures of 600–1100 °C or more (Switzer et al., 2009; Pironi et al., 2011; Switzer et al., 2014). Optimised treatment regimes can significantly reduce the contaminant load of the soil, sometimes to safe levels where re-use can be considered; however, the effects of treatment conditions on soil quality must be understood in order to support re-development after remediation.

Post-remediation effects are particularly important if the soils are to support plant growth for phytoremediation, biomass crop production, habitat restoration, or urban green space. The effects of heating on soil depend on treatment temperatures and the duration of exposure. Even the lower temperatures (~100 °C) utilised in remediation will impact soil biota—killing plant propagules, macrofauna, and microorganisms (Certini, 2005). As treatment temperatures increase, other negative impacts occur, such as charring and subsequent loss of organic matter (Certini, 2005) and atmospheric losses of nitrogen (Glass et al., 2008; Gray and Dighton, 2006). Losses of organic matter and nitrogen will be almost complete for any treatments above 500 °C (Glass et al., 2008; Gray and Dighton, 2006), at which point clay minerals breakdown and aggregate, physically altering the soil (Ulery et al., 1996; Terefe et al., 2008; Ketterings et al., 2000). Physical changes to clay minerals and loss of organic matter severely reduce the soil's ability to retain valuable nutrients (Kang and Sajjapongse, 1980). High temperatures also affect the biological availability of many macro-nutrients such as phosphorus, potassium and calcium by altering geochemistry (Kang and Sajjapongse, 1980; Galang et al., 2010). At very high temperatures (e.g., >1000 °C), less volatile nutrients may become lost to the atmosphere, including phosphorus (Galang et al., 2010). Compiled literature evidence suggests that alterations to chemical conditions depend on remediation temperature.

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While many previous experiments have focused on relatively lower temperatures and discrete target temperatures, few have examined the full-range of temperatures utilised by remediation technologies. Even less frequently have chemical conditions been compared to multiple biological metrics simultaneously. At low heating temperatures (60–350 °C), complicated relationships exist between heating temperature and plant growth (Cébron et al., 2009, 2011). Combining the results of a number of studies, Johnson (1919) observed that heating in this range could unpredictably have both positive and negative effects on growth depending on soil and plant type. At higher temperatures (>400 °C), results seem more consistent. For instance, Kang and Sajjapongse (1980) observed reduced biomass in rice plants grown in soil heated to 500 °C compared to those heated to 200 °C or less. Roh et al. (2000), studying the thermal desorption of mercury, found greater plant growth in soil treated at 350 °C compared to 600 °C, despite higher residual toxin levels. Given the range of temperatures now utilised during thermal and smouldering remediation (ambient to over 1000 °C), evaluation of the effects of soil heating on plant growth over this full range is important to estimate the effects of specific remediation techniques.

In addition to impacts on plants, soil heating can have significant effect on the soils' ability to sustain microbial communities, with consequential impacts on nutrient cycling, organic decomposition, and, in terms of soils with remaining contamination, bio-polishing of residual contaminants (Cébron et al., 2009, 2011; Thion et al., 2012). Successful re-colonisation by microorganisms and plants is essential to sustainable ecosystem recovery. Re-colonisation depends on many factors, but the availability of food (carbon) and nutrients are two key factors. For example, Bárcenas-Moreno and Bååth (2009) observed reduced microbial biomass after 21 days of incubation when carbon levels had significantly been reduced by heating to 400–500 °C. Higher temperatures are even more likely to remove carbon and nutrients, and as a result, microbial re-colonisation of these soils becomes severely inhibited. The extent to which micro-organisms can re-colonise soils, in terms of key-population levels and functional roles, are important in predicting whether long-term viable soil ecosystems are possible without continuous nutritional inputs.

This paper examines how full-range of soil remediation technologies impact *Trifolim pratense* (red clover) and *Festuca rubra* (red fescue), two representative proxies for the effects of thermal and smouldering remediation processes on plants. The red clover was selected for its ability to create rapid vegetative cover, fix atmospheric nitrogen through associations with symbiotic microorganisms, and enhance succession on lithoseric soils (Li and Daniels, 1992; Jefferies et al., 1981). Fescue is a commonly used grass for soil-erosion control and establishing plant growth on bare ground. Changes to soil physical and chemical properties are simultaneously quantified to determine changes to soil characteristics after thermal (105–1000 °C) and smoulder treatments. Microbial community recovery and enzyme activity are examined to establish the soils' capabilities to effectively cycle nutrients. These analyses identify, among the combinations of high temperature treatment and soil types, the ecological impacts to better inform post-treatment interventions to create an effective growing media for the desired land use.

2. Materials and methods

2.1. Soil samples and treatments

We selected two topsoils for this study: an acidic loam (Soil 1) from northeast Scotland, and a commercially available horticultural soil (Soil 2) with a neutral pH. While organic contaminants could contribute to soil structure (Monserie et al., 2009), pristine soils were selected for quasi-baseline purposes. All soils were air-dried and sieved to below 2 mm; soils were then oven dried at 105 °C for three days to remove moisture before being heat-treated at 250 °C, 500 °C, 750 °C and 1000 °C. Basically, 500 g-portions of oven dried soil were spread out in a large crucible, around 4 cm deep, heated in a muffle furnace (Nabotherm P330, Lilienthal, Germany) and then held at temperature for one hour; 15–20 portions were bulked together for each soil-temperature treatment. Air-dried soils, without any further heating, represented experimental controls.

Additional portions of each soil type were artificially contaminated with coal tar (80 g/kg) and treated via smouldering remediation (SM) (Pironi et al., 2009) to evaluate its related effects. Based on Switzer et al. (2009), a heating element and air diffuser were emplaced in around 5 cm of clean sand at the bottom of a 3-l quartz column. The column was filled with contaminated soil until 10 cm of the beaker remained, and another layer of clean sand. A central line of thermocouples was used to monitor smoulder progression. The smoulder process started by heating soils to 300 °C, at which point the air flow commenced and the heater was switched off. Smouldering proceeded until smoke production ceased and temperatures declined, at which time airflow was stopped.

2.2. Soil analyses

Further details of the physical and chemical measurements of soils can be found in Pape et al. (in review). Soil pH (BSI, 2005) and electrical conductivity (BSI, 1995) were recorded using a Multi 7 Mettler-Toledo metre (Columbus, OH, USA) after a two hour extraction in 1:5 soil: water mix. Total organic content was measured by dry ashing at 550 °C for five hours (BSI, 1995). Total nitrogen (BSI, 2001) was measured by quantifying NO_X production during combustion using an Apollo 9000 TOC/TN analyser (Teldayne Tekmar, Mason, OH, USA). Inorganic nitrogen species (NH_4^+, NO_3^- and NO_2^-) were measured colorimetrically: an indophenol blue method for NH_4^+; and a sulfanilic acid method for NO_2^- with a hydrazine reduction step for NO_3^- (ADAS, 1985; Bundy and Meisinger, 1994; Shand et al., 2008). In this study, the only form of inorganic nitrogen present in measurable quantities was ammonium. Available phosphate was measured after an Olsen bicarbonate extraction using molybdate/ascorbic acid colorimetry (ADAS, 1985). Cation exchange capacity (CEC) and exchangeable bases (ADAS, 1985) were measured by sequential leaching with ammonium acetate and potassium chloride; flame atomic absorption (Perkin Elmer AAnalyst 100, Waltham, MA, USA) determined quantity of bases, and CEC was determined colorimetrically (Bundy and Meisinger, 1994). Levels of bio-available copper and zinc were measured by extraction in ammonium-EDTA (ADAS, 1985) and ICP-OES analysis (Thermo Scientific, Hemel Hempstead, UK). Additionally, proportions of clay, silt and sand were measured using wet sieving and sedimentation (BSI, 2009) after dispersion in a sodium carbonate/sodium hexametaphosphate solution.

2.3. Plant growth trials

Each soil and temperature treatment was further divided by different microbial amendments. Soils were initially wetted to 25% v/m with either sterile de-ionised water controls or microbially amended (MA) with 0.1% m/m of commercial mycorrhizal inoculant and 25% v/m of aerated compost tea (ACT). The ACT comprised of compost (500 mL) in 15 L of sterile, deionised water, and juice of one orange; this mixture was aerated for 24 h to encourage microbial growth. The soils were then incubated at 27 °C for seven days before being portioned into 200 ml pots. Replicates of 3–4 pots in each treatment were planted with nine red clover (*Trifolium pratense*) or nine red fescue (*Festuca rubra*) seeds, with additional samples left as unplanted controls. All pots were watered using a wick system to maintain constant moisture content (BSI, 2011) and grown in a growth chamber at 27 ± 2 °C with 16 h of light per day. One week after planting, the plants were thinned to two per pot, and after a further six weeks, they were harvested and the soils stored refrigerated (4 °C) for analysis.

After harvest, the plants were dried at 70 °C and analysed for shoot and root extension and dry mass of the roots, shoots, and leaves. In addition, frozen sub-samples of the leaves were analysed for chlorophyll