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Fire increases dust production from chaparral soils

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ABSTRACT

By altering the physical and chemical properties of a landscape, fire may increase its vulnerability to erosive processes. Whereas sediment transport by surface runoff after fires has been often investigated, less is known about the role of wind erosion in burned terrain. To examine how fire might increase a soil's vulnerability to aeolian transport, intact soil samples were collected from a chaparral landscape in southern California and heated with a propane torch with temperatures ranging from 250 to 1025 °C and for durations of 5–60 min to simulate a variety of burn severities. The samples were then subjected to simulated wind and the amounts of eroded sediment were measured. Results indicate a linear increase in the production of wind-erodible sediment with applied heat up to ~10 MJ/m^2. The increase was not due to a reduction in the threshold shear velocity of the soil surface but, instead, to the role of heat in detaching erodible material. In these soils, organic material may be an important binding agent destroyed at high temperatures. The relationship between fire and erodibility is complex, however, because heating may also help to aggregate soil particles. Experiments performed here also suggest a synergistic effect between fire and rain whereby heated soils are more vulnerable to the erosive power of raindrop impacts. Additionally, the soil heating experiments were used to measure and compare the thermal conductivities of intact and disturbed soils. Finally, it is concluded that soil heating may increase the emission of dust through the detachment of erodible particles, a result that may help in the anticipation of respiratory problems for those living downwind of burned areas.

1. Introduction

Fire alters the physical and chemical properties of a landscape (e.g., DeBano, 1981; Cerda, 1998; Cannon, 2001; Shakesby and Doerr, 2006; Gabet and Sternberg, 2008). Whereas the dramatic impact of these changes on a landscape's erodibility by water have been well-documented (e.g., Moody et al., 2013), fire may also increase its erodibility by aeolian processes. As a first order effect, the combustion of protective vegetation leaves the soil exposed and vulnerable to the erosive stress of the wind (e.g., Zobeck et al., 1989; Vermiere et al., 2005; Sankey et al., 2009a, 2010; Miller et al., 2012). Whicker et al. (2002), for example, measured wind velocities and vertical soil fluxes at burned and unburned sites in desert shrubland and found significantly higher rates of aeolian transport from the burned sites. They concluded, however, that the effects of the fire went beyond a reduction in plant cover and proposed it had increased the erodibility of the soil.

Fine particles in soil are held together by a variety of binding agents (Giovannini et al., 1988) to form larger aggregates that are relatively resistant to wind erosion. However, with soil surfaces exposed to temperatures at least as high as 700 °C during fires, these natural cements may be destroyed (DeBano et al., 1979). Organic matter, in particular, is an important binding agent and it begins to be lost from soils when temperatures exceed ~250 °C (DeBano et al., 1979; Giovannini et al., 1988). Indeed, biological soil crusts (BSC), communities composed primarily of cyanobacteria, lichens, green algae, mosses, and fungi, are instrumental in aggregating soil with filaments that bind particles together and through the production of polysaccharides that act like a glue (Belnap et al., 2001; Bowker et al., 2004; Mager and Thomas, 2011). For example, Bowker et al. (2004) found a loss of aggregate stability in burnt prairie soils and attributed the change to a damaged BSC, although they concluded that the low-intensity fires common to their field site were probably not hot enough to completely destroy it. Compounds added to the soil during fires may also increase its erodibility by wind. Ravi et al. (2006, 2009) determined that the formation of a hydrophobic layer on the soil surface, a product of combusted vegetation, can decrease the threshold shear velocity of soil particles. The heating of a soil, however, does not necessarily lead to an increase in its erodibility. Giovaninni et al. (1988) and Giovannini and Lucchesi (1997) documented a reduction in the fine fraction of soils as they were heated and concluded that the coarsening was due to the fusion of clay particles. In addition, Giovaninni et al. (1988) found that heating of the soils led to the recrystallization of iron and aluminum compounds, a fire-induced laterization, that strengthened soil aggregates. Both of these changes would increase a soil's resistance to aeolian transport.

The need for understanding the relationship between fire and the erodibility of soils is particularly acute in the flammable terrain of southern California. In this region, large fires are often stoked by the seasonal

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Santa Ana winds which typically blow from September to March and can reach hurricane speeds (Raphael, 2003). Because these meteorological conditions persist for many months, burned areas are continuously subjected to strong winds that can blow large dust clouds westward over heavily populated areas (Fig. 1). Dust is a lung irritant (e.g., Morman and Plumlee, 2013) and there is speculation that these events lead to an increase in respiratory problems throughout the Los Angeles basin (G. Plumlee, pers. comm.). Fire-related dust from this region may also serve as a source of nutrients and iron to the nearshore marine environment, potentially stimulating the growth of phytoplankton (Bishop et al., 2002). The ecological effects of this dust appear to extend as far as the Channel Islands, 100 km off the coast of Los Angeles (Fig. 1). Significant amounts of dust, blown from the mainland, have been found on these islands, and the silt component of the dust is thought to be an important medium for sustaining their endemic plant populations (Muhs et al., 2008). The author visited the site of the 2006 Esperanza Fire (Fig. 1) during a period of Santa Ana conditions and noticed that the high winds had stripped the upper 1–2 cm of soil from the tops of burned ridges; whereas the dust had been blown away, the coarser material was forming 2–3 cm high sand ripples. The fire-wind sequence, therefore, has the potential for large-scale erosion and redistribution of material.

To examine the role of fire in aeolian soil erosion, this work investigated how the heating of soils affects its erodibility. Intact soil samples were removed from unburned sites in southern California and heated at a range of temperatures and for varying amounts of time. The samples were then installed in a wind tunnel and dust concentrations (PM_{10}) were monitored. Samples were also placed in a 'wind-box' which captured all the sediment displaced by simulated wind to measure the total production of material.

2. Materials and methods

2.1. Soil sampling

The soil samples were collected in the San Jacinto Mountains (lat. 33.9008, long. −116.8688), 120 km west of Los Angeles (CA) at an elevation of 948 m (Fig. 1). Local mean annual rainfall is 49 cm and annual mean high temperature is 25.6 °C. The bedrock is granitic and the slopes are vegetated by members of the chaparral community, primarily black sage (*Salvia mellifera*), white sage (*Salvia apiana*), and California sagebrush (*Artemisia californica*). The sampling site, 1 km from the perimeter of the 2006 Esperanza Fire, was along a ridge bounded by steep, often rocky, slopes. The shallow soil is a rocky sandy loam categorized as a Typic Xerorthent with an organic matter content of 0.8% (Beaudette and O'Geen, 2009). Particle size analysis with a Micromeritics Sedigraph 5100 (Norcross, GA, USA) of five samples indicated that the soils had clay contents of 15–20%.

A custom-made 'cookie cutter' with sharpened edges was used to cut out, to a depth of 5 cm, intact 10 × 10 cm samples of the soil surface (Fig. 2). The soil blocks were carefully placed in commercially available cheesecake pans with removable bottoms. Upon returning from the field, the samples were stored in cool, dry conditions. Prior to analyzing the soil samples, litter and vegetation were carefully removed from the surface with nail clippers and tweezers. Although retaining the litter and vegetation may have increased soil hydrophobicity and affected the erodibility of the soils in a way that might simulate field conditions (Ravi et al., 2006, 2009), the goal of this project was specifically to investigate the role of soil heating. Litter and vegetation on the soil would have shielded the surface from the flame to some unknown degree and smoldering organic material might have added some heat that I would not have been able to control or measure. Finally, loose soil on the sample surfaces was removed with gentle puffs of air to isolate the ensuing treatments as the source of erodible material.

2.2. Soil treatments

2.2.1. Soil heating

A propane torch was used to simulate the delivery of heat from a wildfire (Fig. 3). Flames from the torch reached down to the surface of the soils, where the temperature was monitored with a K-type thermocouple and recorded with a datalogger. A calorimeter was used to calibrate a relationship between the temperature at the soil surface (T; °C) and the heat flux (ϕ; W/m^2). This relationship was found to be: $\phi = 17.8$ T–4999 (n = 5; $R^2 = 0.94$; $p < 0.05$). The magnitude of the heat flux into the soil samples by the torch (order 10^3 W/m^2) is similar to values estimated by Massman et al. (2003) for downward heat fluxes into soils from forest fires (2300–3000 W/m^2).

Each soil sample was heated at a constant temperature for a set time; temperatures and durations were varied between samples. The range of testing conditions was based on the limited soil surface temperatures recorded during prescribed burns (DeBano et al., 1979). Heating temperatures used were: 250, 350, 450, 500, 550, 650, 750, 800, 875, 975, and 1025 °C. The intervals between each temperature setting were somewhat uneven because of the difficulty in precisely adjusting the pressure regulator on the propane torch. The set of heating

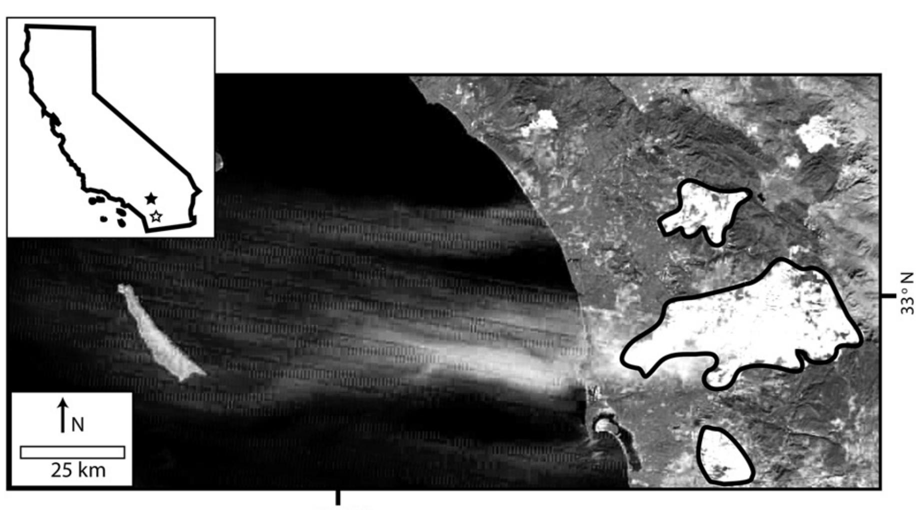

Fig. 1. Dust from burn scars (outlined in black) in southern California (2003). From top to bottom: Paradise Fire, Cedar Fire, Otay Fire. Dust, shown as white clouds, can be seen reaching one of the Channel Islands. Image created from MODIS (Moderate Resolution Imaging Spectroradiometer) data. (Inset) State of California; open star marks location of 2003 fires in MODIS image; filled star marks soil sampling location near Esperanza Fire site.