

Fire effects on cation exchange capacity of California forest and woodland soils



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ABSTRACT

During natural and prescribed fires, combustion of heavy surface fuel loads can expose underlying soil to high temperatures causing thermal alteration of soil minerals and other changes in soil properties. We studied the effect of fire on soil cation exchange capacity (CEC) by comparing severely burned soils to nearby unburned soils at five forest and woodland sites in California, USA. Combusted logs and heavy fuel produced reddened zones of thermally altered soil underlain by blackened zones where heat exposure was lower. The cation exchange capacities of the reddened soils were 57 to 82% lower than the unburned soil while the blackened soils had 31 to 53% less CEC than unburned soil. The reddened soil experienced the highest burning temperatures resulting in the loss of organic carbon (OC), the conversion of goethite to maghemite or hematite, the destruction of kaolin, and dehydroxylation and permanent collapse of vermiculite and chlorite. Overall, most of the CEC loss was due to thermal destruction of soil organic matter (SOM), but this CEC will be restored in the post-fire ecosystem succession as biomass re-accumulates and rebuilds soil humus. The loss of CEC due to mineral alteration is longer lasting, though limited in spatial extent.

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1. Introduction

Fire is a natural phenomenon in many wildlands, particularly in the semiarid and temperate forests and woodlands of the western United States (Dillon et al., 2011; Marlon et al., 2012). Fire suppression practices during the past century have increased tree densities and produced unnatural accumulations of leaf litter and downed woody debris, which now fuel larger more intense wildfires (Miller et al., 2009). Prescribed burns are increasingly used by land managers to reduce heavy fuel loads (Stephens et al., 2014). Burning of organic materials and the resulting heat pulse into the underlying soils can significantly alter soil properties, though the extent of alterations depends on the amount and type of fuel, moisture content, temperatures generated, and burn duration (Certini, 2005). While many fire-induced changes in soil properties are of short duration (e.g., Graham et al., 2016), others last much longer (e.g., Ulery et al., 1996).

Among short-term effects, burning of organic matter on the surface of the soil is the most obvious. Both O horizons and coarse woody debris are consumed to varying degrees by fire, but they often accumulate

again within decades due to net primary productivity as the ecosystem recovers after the fire (Certini, 2005).

When surficial organic matter is completely combusted, white ash is produced. White ash consists of oxides of the cations contained in the organic matter (e.g., CaO) and has a pH in the range of 10 to 12. Within weeks, the oxides become carbonated due to exposure to moisture and atmospheric CO₂, producing dominantly CaCO₃ and a pH of about 8.2 (Bodi et al., 2014). The presence of combustion-produced CaCO₃ elevates the pH of normally acidic A horizons.

Humified organic matter and roots in soil A horizons can be affected by the heat pulse from fire at the surface. When soil is heated above 500 °C, soil organic matter is completely combusted and all carbon is volatilized and lost (Bodi et al., 2014). At lower temperatures, in the range of 250 to 500 °C (Certini, 2005; Bodi et al., 2014), the humified organic matter and roots are altered to char (black carbon).

The most severe alterations of soil properties occur where high temperatures are maintained for a long time. These conditions are produced by the combustion of coarse woody materials, such as logs or stumps. While these concentrations of coarse fuels typically cover only a few percent of forest floors, their combustion may have long-term cumulative effects on soils (Ulery and Graham, 1993; Goforth et al., 2005). Intense heating from the burning of coarse fuels can alter soil minerals or even completely destroy them. The yellow-brown iron oxyhydroxide, goethite, a very common soil mineral, is altered to reddish hematite or maghemite at about 300 to 400 °C. Maghemite is the more likely product

Abbreviations: CEC, cation exchange capacity; OC, organic carbon; SOM, soil organic matter; XRD, x-ray diffraction.

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if the thermal conditions are oxygen deficient (Schwertmann and Taylor, 1989), as may occur in the subsurface soil environment. Another common soil clay mineral, kaolin, is thermally decomposed at about 420 to 550 °C, yielding amorphous aluminosilica material that can cement clay-sized particles together forming inorganic aggregates (Ulery and Graham, 1993; Ulery et al., 1996). Expansive phyllosilicates (i.e., vermiculite or montmorillonite) can be irreversibly collapsed or thermally decomposed at high temperatures (Sarıkaya et al., 2000; Ulery et al., 1996).

Cation exchange capacity is a critical soil property that provides storage for nutrient cations. The sources of soil CEC are organic matter and clay minerals (Bourg and Sposito, 2012), both of which can be severely altered or destroyed by heat from fires. The loss of SOM and alteration of phyllosilicates during intense burning may result in lower CEC in the surface soil, which is particularly evident in sandy or coarse-textured soils (Zavala et al., 2014). In a laboratory heating study, Inbar et al. (2014) reported that the CEC decreased when soils were heated to 300 °C due to particle size changes resulting from dehydration of 2:1 clay minerals and the loss of organic matter. Ulery and Graham (1993) also found coarser textures due to the formation of aggregates and the dehydroxylation of clay minerals in some severely burned soils. Biochar CEC was correlated with the ratio of oxygen to carbon atoms and decreased during fast pyrolysis at 700 °C, reportedly due to the loss of hydroxyl, carboxylate, and carbonyl groups (Lee et al., 2010). Other laboratory studies have shown almost complete destruction of CEC in soils exposed to extremely high temperatures (Sarıkaya et al., 2000; Soto and Diaz-Fierros, 1993).

Fire may also lower CEC by destroying the soil organic matter. The CEC of pine forest soils in Turkey two weeks after burning was 40% lower than that of nearby unburned soils, but CEC returned to pre-fire levels within one year (Yildiz et al., 2010). Loss of CEC was attributed to thermal destruction of soil organic matter, and recovery of CEC to re-accumulation of soil organic matter. Soil CEC decreases have been reported in a variety of environments affected by burning. The objectives of this study were to determine if soil CEC was impacted by severe burning of wildland soils in California and, if so, to interpret the cause of the change in CEC. Our hypothesis was that thermal alteration of soil clay minerals and loss of organic matter in surface soil would decrease the CEC.

2. Materials and methods

Soils at five wooded sites distributed across the length of California were sampled in this study (Fig. 1). More details on the sites, field sampling methods, and soil properties have been presented previously for

SRP, SNF, and KNF (Ulery and Graham, 1993; Ulery et al., 1993; Ulery et al., 1996) and SPK and MPK (Goforth et al., 2005). Four of these sites burned in wildfires and one (SRP) was a prescribed burn. Mean annual precipitation ranged from 360 mm for the oak woodland site in southern California to 1260 mm at a mixed conifer site in northern California (Table 1). The soils formed from a range of intrusive igneous rocks on relatively low gradient slopes (2–24%). The soils are Ultic Haploxeralfs, except at the oak woodland site (SRP) where they are Lithic Haploxerolls. Surface soil textures were sandy loams, except at the SNF site, which was a loam (Table 2).

The five sites varied in how recently they had burned, but all of them included areas of severe, high intensity burning under heavy fuel loads and lightly burned areas of apparently undisturbed soil within a few meters of each other. Even in prescribed burns, heavy isolated fuel loads such as tree trunks and slash piles can heat the underlying soils to temperatures high enough to alter soil properties. Although each sampling area experienced a single fire event, the uneven distribution of fuel and burning left areas where surface litter was still intact and no evidence of soil alteration was seen, hence we refer to these soils as “unburned”.

Samples were taken from vertical cross sections excavated through the soil where logs or limbs had completely combusted. These soil cross section profiles exposed the characteristic morphology of severely burned soils (Ulery and Graham, 1993): a 1- to 10-cm-thick reddened layer underlain by a 1- to 15-cm-thick blackened layer further underlain by unaltered soil (e.g., Fig. 2). Nearby unburned soil material was collected from depths similar to the reddened and blackened soil zones for comparison of changes in CEC.

The soil samples were air-dried and sieved to remove rock fragments >2 mm in diameter. Air-dried samples were stored in the dark at room temperature until CEC was determined. Color was measured using a chromameter (model CR-200, Minolta Corporation, Ramsey, NJ, USA). The redness rating was calculated according to the formula:

$$\text{Redness Rating} = (10 - \text{YR hue}) \times \text{chroma} / \text{value}.$$

Soil pH was measured on a 1:1 sample:water ratio. Organic carbon was calculated by subtracting the inorganic carbon contributed by calcium carbonate, measured manometrically (Loeppert and Suarez, 1996), from the total carbon, which was determined by measurement of evolved CO₂ during dry combustion (Nelson and Sommers, 1996). Cation exchange capacity was measured by NaOAc saturation followed by NH₄OAc extraction (U.S. Salinity Laboratory Staff, 1954). The CEC measurements were made with solutions adjusted to pH 6, which approximates the pH of unburned A horizons in the study areas, and pH 8.2,

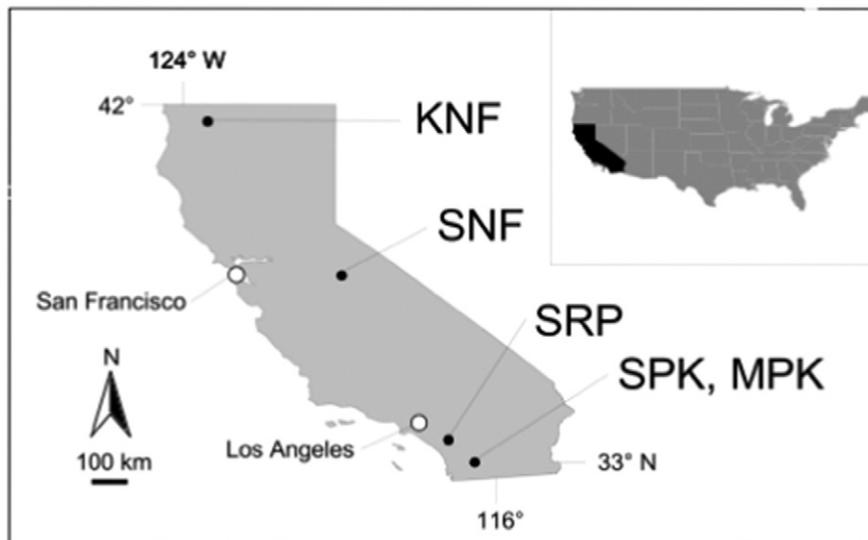


Fig. 1. Locations of the study sites in California.

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