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Soil carbon pools and fluxes vary across a burn severity gradient three years after wildfire in Sierra Nevada mixed-conifer forest

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ABSTRACT

Carbon (C) storage in soils contributes to the strength and stability of total ecosystem C sinks, but both aboveground and belowground C is vulnerable to loss during fire. The distribution of soil C and nitrogen (N) among various defined pools – e.g., active, slow and resistant C, and ammonium and nitrate as forms of inorganic N – determines the C storage capacity of forests and the nutrient availability for plant communities recovering from wildfires. Projections of increased wildfire severity due to a warming climate and frequent droughts raise concerns about parallel increases in fire's impacts on the sizes and mineralization kinetics of soil C and N pools, with potentially long-lasting effects on the strength of the forest C sink and on the ability of forests to recover from disturbance. Therefore, we sought to determine how the sizes and mineralization rates of soil C and N pools vary across a gradient of fire severity three years after the Chips Fire burned 30,500 ha of Sierra Nevada mixed-conifer forest. We measured total C and N in forest floor and mineral soil (0–5 cm), the pool sizes and mean residence times of the active, slow, and resistant C in mineral soil, and the pool sizes and mineralization rates of inorganic N in mineral soil. Forest floor total C was lower in areas that experienced high severity fire than in unburned reference areas, an effect likely attributable to greater combustion of forest floor material in high severity areas. Mineral soil C content did not vary with fire severity. Over a 300-day lab incubation, mineral soil CO_2-C efflux rates were consistently lower in soils from areas that experienced high severity fire relative to unburned reference areas and were associated with longer mean residence times of the slow C pool. Forest floor N content was lower in high severity areas than unburned areas, whereas mineral soil total N did not vary with fire severity. Mineral soil ammonium and total inorganic N concentrations increased significantly with fire severity in field-fresh soils, but this trend was no longer apparent after a 300-day lab incubation, indicating that site-specific factors control N availability among fire severity levels. Our results indicate that future increases in wildfire severity in mixed-conifer forest may alter the strength of the forest C sink by impacting the amount C stored in forest floor, the stability of mineral soil C, and the availability of N to recovering plant communities.

1. Introduction

Changes to the size and persistence of soil carbon (C) pools in temperate forests have the potential to influence atmospheric CO_2 concentrations (Lutzow et al., 2006; Trumbore, 2000) because of the major role these ecosystems play in global C dynamics. For example, temperate forests accounted for ~30% of the global forest C sink from 1990 to 2007 (Pan et al., 2011), and store 48% of ecosystem C in their soils (Pan et al., 2011). The majority of soil C is stored as soil organic matter (SOM), a continuum of materials that remains in soil for days to centuries, depending on the physiochemical properties of the SOM and the surrounding matrix, and the physical accessibility of the organic compounds to decomposers (Schmidt et al., 2011). The SOM continuum is often modelled as three distinct C pools with variable turnover times: an active C pool (C_a) with a mean residence time (MRT) of days to months, a slow pool (C_s) with a MRT of years to decades, and a resistant pool (C_r), potentially stable for centuries (Paul et al., 2006; Trumbore, 1997). The turnover rates and distribution of C among these three C pools are sensitive to changes in environmental conditions and disturbance regimes (Jackson et al., 2017; Trumbore, 1997) and influence the strength of the ecosystem C sink (Luo and Weng, 2011).

Wildfires are one of the most common forest disturbances in the conterminous United States, burning > 17,000 $km^2 y^{-1}$ and causing 13.40 Tg C y^{-1} of direct C emissions during 1990–2012 (Chen et al.,

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2017). In addition to causing combustion emissions, high-severity wildfires can transform forest stands from C sinks to C sources when C losses via decomposition exceed photosynthetic C gains during post-fire forest recovery (Kashian et al., 2006). When climate and fire regimes are stable, wildfire emissions are balanced by the C uptake of vegetative regrowth during ecosystem recovery, ecosystems transition from C sources back to C sinks, and the net ecosystem C flux is zero (Bowman et al., 2009; Loehman et al., 2014). However, altered disturbance regimes disrupt this equilibrium by affecting the magnitude of C losses and temporal patterns of ecosystem recovery (Luo and Weng, 2011). Fire regimes have shifted in ecosystems worldwide: for example, the global average area burned increased by > 20% in the second half of the 20th century compared to the first half (Flannigan et al., 2013). In western United States forests (west of 102° W longitude), wildfire frequency increased four-fold, total area burned increased six-fold, and the length of the fire season increased by 78 days during 1987–2003 compared to 1970–1986 (Westerling et al., 2006). In the Sierra Nevada mountain range, the proportion of burned area that experienced high severity fires nearly doubled between 1984 and 2006 (Miller et al., 2009b).

Wildfire severity is a measure of the magnitude of effects of wildfire on ecosystem biomass (Keeley, 2009), and is correlated with C stock losses from aboveground vegetation and dead wood in mixed-conifer (Campbell et al., 2007; Meigs et al., 2009) and ponderosa pine (*Pinus ponderosa*) forests (Meigs et al., 2009). The increasing occurrence of high burn severity in an ecosystem that historically experienced frequent fires of primarily low to moderate severity has the potential to alter forest composition and successional pathways and destabilize forest C stocks, particularly when coupled with the warming temperatures and increased drought frequency expected in climate projections (Earles et al., 2014; Liang et al., 2017). Landsat-derived spectral data available since 1982 have greatly expanded the scale and ease with which burned areas can be mapped (García and Caselles, 1991). The increasing availability of fire severity data has expanded both interest in and ability to assess the impacts of fire on aboveground components of the ecosystem, whereas the ability to determine effects on belowground C stocks remains challenging because Landsat imagery is more sensitive to changes in vegetation than soil (Miller et al., 2009a; Miller and Thode, 2007). The storage of C in pools with long residence times increases the strength and stability of the total ecosystem C sink (Luo and Weng, 2011). Thus, the size, structure, and turnover times of soil C pools have potential to influence the transition of forests from C sources to C sinks during recovery from wildfire and may either moderate or exacerbate the response to shifting patterns of fire severity.

Meta-analyses have indicated that wildfires in general decrease soil C stocks in the forest floor layer (Nave et al., 2011), but the response of mineral soil C varies with climatic zones, forest type, soil depth, fire type (i.e., wildfire vs. prescribed fire), and time since fire (Johnson and Curtis, 2001; Nave et al., 2011; Wang et al., 2012). Wildfire-induced changes in soil N stocks generally mirror those of soil C stocks in temperate regions, in which forest floor N stocks generally decrease (Nave et al., 2011; Wang et al., 2012), whereas the effects on mineral soil N vary with soil depth and fire type (Nave et al., 2011; Wan et al., 2001). None of the meta-analyses to date have directly assessed the impacts of fire severity or fire intensity (i.e., energy flux resulting from a fire) on soil C and N, a shortcoming acknowledged by several researchers (Nave et al., 2011; Wang et al., 2012). However, studies that separate the effects of prescribed fires and wildfires on soil C and N have found that wildfires cause greater losses to forest floor C and N stocks and mineral soil C concentrations than prescribed fires (Nave et al., 2011; Wang et al., 2012). Because prescribed fires are often of lower intensity and result in lower severity relative to wildfires, the differences in impacts between prescribed fires and wildfires reported to date suggest that soil C and N storage may also differ across contrasting levels of fire severity (Alcañiz et al., 2018).

Because of the large proportion of C stored in soil, the size and turnover times of the C_a, C_s, and C_r pools determines the strength and stability of the ecosystem C sink in recovering forests (Luo and Weng, 2011). Fernández et al. (1999) used a two-pool model to assess the impacts of wildfire on labile and recalcitrant soil C pools and their associated kinetics in *P. sylvestris* and *P. pinaster* forests in northwest Spain and found that wildfire increased the size and mineralization rate of the labile C pool in soils to 5 cm depth, an effect that persisted for several months, but was no longer apparent after one year. Two years after the wildfire, the labile C pools in burned soils and their mineralization rates were lower than or equal to those in unburned soils; meanwhile, the mineralization rate of the recalcitrant C pool in burned soils was consistently lower than that of unburned soils over the two year study (Fernández et al., 1999). The study sites Fernández et al. (1999) used experienced only high intensity fires, and the effects of fire severity level were not considered. To our knowledge, the relationship between wildfire severity and the C_a, C_s, and C_r pools and their associated kinetics has yet to be assessed: this information is important for understanding long term effects of wildfire on forest C storage (Birdsey et al., 2006). For example, lower mineralization rates and larger sizes of the C_r and C_s pools may partially offset total ecosystem C losses by increasing the overall MRT, and thus the sink strength, of forest C (Luo and Weng, 2011).

Fire directly influences the soil C pool structure through the formation of pyrogenic carbon (i.e., carbon associated with char; PyC), which is generated via the thermal decomposition of biomass and encompasses a spectrum of materials from slightly charred plant matter to highly condensed soot and micrographine sheets (Bird et al., 2015). PyC was initially viewed solely as a resistant C pool, but emerging evidence shows that PyC consists of an active, slow, and resistant pool (Kuzyakov et al., 2014). The relative sizes of these PyC pools depends on combustion temperature (Bird et al., 2015) and source material (Hatton et al., 2016; Michelotti and Miesel, 2015), and the amount of PyC generated during fires has been shown to increase with fire severity (Maestrini et al., 2017; Miesel et al., 2015) and fire intensity (Czimczik et al., 2003; Sawyer et al., 2018). Pyrogenic C contributes directly to soil total C pools, but also influences soil C pools indirectly via impacts on mineralization kinetics of native soil C. For example, PyC induces short-term positive and long-term negative priming effects (Maestrini et al., 2015), and soil C mineralization rates decrease with increasing PyC concentrations (Michelotti and Miesel, 2015). Thus, severity-based differences in PyC accumulation may have downstream impacts on C flux rates from the soil to the atmosphere.

Low soil inorganic N content often limits plant productivity in coniferous forests (Vitousek and Howarth, 1991), whereas enhancing N availability can increase soil C stocks by increasing soil C inputs (Nave et al., 2009) and decreasing C loss via respiration (Janssens et al., 2010). Therefore, the sizes of inorganic N pools in post-fire soils are likely to affect the recovery of aboveground (Grogan et al., 2000) and belowground C stocks. Increases in soil ammonium (NH_4^+) and nitrate (NO_3^-) concentrations are typical after wildfires, across a variety of ecosystem types (Wan et al., 2001). Maximum increases in soil NH_4^+ and NO_3^- concentrations are approximately tenfold greater than pre-fire conditions, generally returning to pre-fire levels after one year for NH_4^+, and within five years for NO_3^- (Wan et al., 2001). Studies ranging from two days to 26 months after fires have variously attributed the N pulse to pyrolysis of forest floor material (Covington and Sackett, 1992), ash deposition (Christensen, 1973), decreased uptake by vegetation due to plant mortality (Ficken and Wright, 2017), and decreased uptake by microbes (Koyama et al., 2012).

Fire also impacts N cycling in soil, over short- and longer time periods after fire. For example, a meta-analysis of N mineralization response to fires showed that fires stimulate a short term (< 3 months) increase in N mineralization, but decrease N mineralization rates over the long term (at least 3 years), a decrease that is greater for prescribed fires than wildfires (Wang et al., 2012). In addition to the direct effects of increased N availability on N mineralization rates, changes to N