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Forest burning affects quality and quantity of soil organic matter

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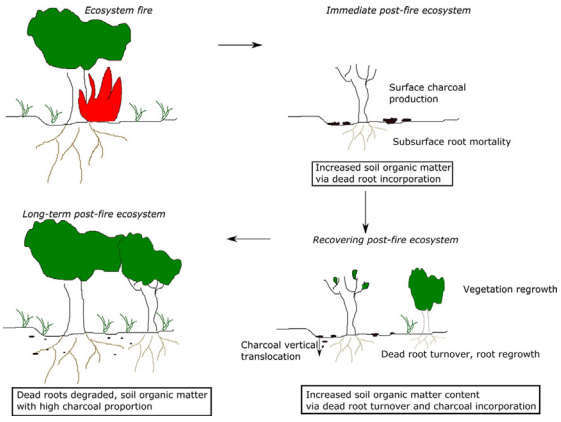
HIGHLIGHTS

- Forest fire removes above ground biomass and generates charcoal.
- Fire induces short-term enrichment of non-charcoal soil organic matter.
- Charcoal is rapidly incorporated into the soil profile.
- Longer-term retention results in high charcoal proportion of soil organic matter.

GRAPHICAL ABSTRACT



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ABSTRACT

Fire alters ecosystem carbon cycling and generates pyrogenic matter such as charcoal, which can be incorporated into soils. The incorporation and cycling of charcoal in soils is a potential carbon sink, but studies investigating charcoal and carbon dynamics in soils are still lacking. We investigated soil carbon, charcoal and nitrogen dynamics in the top 20 cm of a sandy soil within a eucalypt forest in eastern Australia at three sites representing a chronosequence from 3 months to 14 years post-fire. In the short-term, fire removed litter, but resulted in an increase in both the charcoal and non-charcoal SOC content of the soils, which we attribute to above-ground charcoal generation and its incorporation into the soil profile, as well as below-ground root mortality. On a decadal timeframe, charcoal was preferentially retained in the sandy soil, in which other stabilisation mechanisms are limited, so that the influx of dead root carbon had no remnant effects. The incorporation and retention of charcoal in the soil profile is highly important to carbon cycling in such sandy soils with high fire frequency. It is highly likely that these effects are not limited to the upper 20 cm of soil and future studies should investigate deep soil charcoal cycling.

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1. Introduction

Fire has affected ecosystems for millions of years, with geological evidence of fire dating back to soon after the appearance of terrestrial plants in the Silurian (420 million years ago) (Bowman et al., 2009). The influence of fire is not limited to immediate effects on biota, but fire also impacts the global carbon cycle, transferring approximately 2.5 Pg of carbon (as CO_2) equivalent to ~4% of net primary productivity to the atmosphere per year (van der Werf et al., 2006). Fire removes a portion of the above-ground biomass in affected burnt areas (Alexis et al., 2007; Czimczik et al., 2003), converting the majority of affected biomass into CO_2.

Although the removal of biomass via fire might be expected to result in a reduction in organic inputs into the soil and a decline in soil organic carbon (SOC), the effects of fire on soil organic matter (SOM) content remain uncertain. Fire intensity and frequency, vegetation type, fuel load, and soil physical and chemical parameters influence the direction and magnitude of SOM response to ecosystem burning (Knicker, 2007). Losses of 40–50% of SOC in the top 5 cm of soil have been reported due to repeated burning, with the magnitude of loss increasing with fire frequency (Bird et al., 2000). On the other hand, elevated primary production after fire within fire-adapted ecosystems may mitigate initial carbon loss through combustion, leading to an increase in SOC storage (Dai et al., 2005).

The action of fire on organic matter produces chemically altered residues known as pyrogenic matter (Preston and Schmidt, 2006), and the carbon within this pyrogenic matter is referred to as pyrogenic carbon or black carbon. Charcoal is a visually defined, macroscopic component of pyrogenic matter. Chemically, pyrogenic matter consists largely of highly condensed polyaromatic rings, which are believed to be recalcitrant (i.e. resistant to degradation), and may be retained in soils for millennial time periods (Hobley et al., 2013; Schmidt and Noack, 2000).

It has been hypothesized that, due to its extended residence time in soils, incorporation of recalcitrant pyrogenic carbon into the soil profile may allow fire-affected ecosystems to recover to a state of higher carbon storage than in the pre-fire condition (Krull et al., 2003; Preston and Schmidt, 2006). However, rapid cycling of charcoal in soils has also been reported (Bird et al., 1999; Singh et al., 2012) and partial degradation of pyrogenic carbon has been shown to occur during short-term laboratory incubations (Hilscher et al., 2009), suggesting that pyrogenic carbon may not always be stable. Additionally, interactive priming of pyrogenic and non-pyrogenic carbon may promote higher degradation of both carbon pools (Hamer et al., 2004). As such, overall effects of fire on SOC may be negligible, at least at the soil surface (López-Martín et al., 2016). These conflicting results highlight the need for more studies into the effects of fire on carbon dynamics in soils and the fate of pyrogenic carbon in the environment.

Pyrogenic matter which remains at or near the soil surface can be consumed by subsequent fires (Czimczik and Masiello, 2007). In systems where fires recur, pyrogenic carbon must therefore be incorporated into the soil profile in order for it to be retained for long time periods. The incorporation of pyrogenic matter into soils is probably a function of both soil and environmental conditions. Soil characteristics such as texture and mineralogy determine the physical and chemical soil environment (e.g. pore-size distribution and surface reactivity), influencing rainwater infiltration and erodibility but also biotic soil properties (e.g. ant and earthworm activity). Climate influences fire frequency (directly via temperature and indirectly via vegetation and fuel load), but also the vertical redistribution of pyrogenic matter via percolation with rainwater (Hobley et al., 2016). Although there is evidence of enhanced subsurface carbon storage attributable to pyrogenic matter (Dai et al., 2005; Hobley et al., 2014; Velasco-Molina et al., 2016), estimates of translocation rates vary (Carcaillet, 2001; Leifeld et al., 2007) and may be depth dependent (Major et al., 2010).

In this study we investigated the effects of fire on the amount and vertical distribution of SOC, soil nitrogen (N), and soil charcoal content in post-fire environments in a eucalypt forest of eastern Australia. We hypothesized that fire would lead to an enrichment of charcoal within the upper soil profile, with the effects being most pronounced nearest the soil surface. Further, we hypothesized that over time, charcoal incorporation into the soil profile would result in enrichment of charcoal at greater soil depths. This effect combined with carbon production due to ecosystem recovery would result in a positive relationship between post-fire recovery period and overall SOC storage. We tested these hypotheses by analysing litter and soil samples obtained from four depths of three post-fire sites of differing recovery times using a combination of physical (mass, bulk density) and chemical (LECO dry combustion, infrared spectroscopy) analyses.

2. Materials and methods

2.1. Site and soils

Soil and litter samples were collected in September 2014, from Guy Fawkes River National Park, located on the Northern Tablelands of New South Wales, Australia (29°57′S, 152°14′E, Fig. 1). The National Park covers 100,590 Ha of predominantly gorge country, of which ~85% is declared wilderness, dominated by tall open eucalypt forest (New South Wales Office of Environment and Heritage, 2009). The climate is temperate, but varies within the park due to the large variation in elevation, ranging from ca. 200 to nearly 1400 m. The climate statistics for the two nearest meteorological stations (Glen Innes and Dorrigo) report mean annual rainfall of between 1000 and 1980 mm yr^{-1} with mean annual maximum temperatures of 19.1–19.9 °C and minimum temperatures of 7.2–9.9 °C (Australian Bureau of Meteorology, 2016). Fires are common, recurring on a decadal basis. National Park management implements hazard reduction burning with a fire regime aimed at maximising conservation of the natural ecology whilst minimising the risk of uncontrolled fires.

The sampling area was located at an elevation of ~1095 m, had a northerly aspect, moderate gradient (~8%) and was vegetated by a eucalypt dominated open to low open forest. The area was not located directly near any lookouts or major tourist walking tracks so human disturbance of the sampling sites is minor. The soil was frequently shallow (<10 cm) with leucogranite substrate exposed from the soil surface in granite tors. This substrate weathers to a sandy, silicate-rich topsoil. Shallow profiles were classified using the Australian Soil Classification (Isbell, 2002) as Rudosols (Regosols in the World Reference Base, IUSS Working Group WRB, 2015) and deeper soil profiles (>50 cm) were classified as Chromosols (WRB Lixisols), characterised by an abrupt textural contrast to clay-rich subsoil between 40 and 60 cm.

Two tracks (a vehicle track and a fire trail) separate the sampling area into three sites, which are located within 200–500 m of each other but have different fire management histories (Fig. 2). All three sites were intensely burnt in uncontrolled bushfires in the summers of 1995 and 2000. Since then, two sites have been subjected to hazard reduction burning, whereas one has been left to regenerate. The eastern site (B14) had not been burnt since the bushfire 14 years prior to sampling. The western site (B1) was burnt in a controlled hazard reduction fire in July 2013, one year prior to sampling. The central site (B0) has been subjected to two prescribed fires since the 2000 bush fire: the first in July 2007, and the second in June 2014, three months prior to sampling. Due to their immediate proximity, the soil, climate, vegetation, relief, aspect and topography, as well as previously (unmanaged) fire history is effectively identical between sites, so that these sites provide an ideal contrast to test the effects of burning and regeneration time on soil properties.

At each site, samples were collected randomly from within three sampling squares (25 m^2). To account for potential slope effects, the sampling squares were set up at three different slope locations (upper, mid, lower slope, 50–100 m apart) and slope positions were matched between sites. Within each square, five samples of surface organic