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Soil carbon in Australian fire-prone forests determined by climate more than fire regimes

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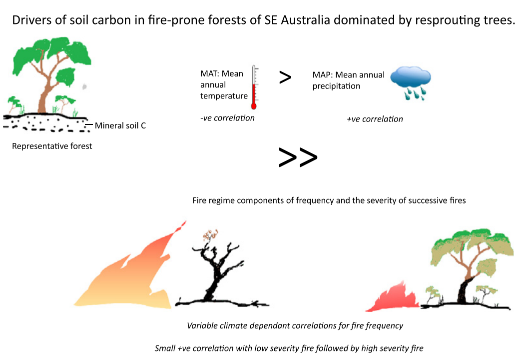
HIGHLIGHTS

- Fire regime and climate factors considered as drivers of soil C pools.
- Lower mean annual temperature was the strongest determinant of total soil C.
- Intermediate fire frequency drove higher soil C in 2 of 3 climate scenarios.
- Higher soil C observed when low intensity fire was followed by high intensity fire.
- Recalcitrant pyrogenic C was a constant portion of the total C pool.

GRAPHICAL ABSTRACT



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ABSTRACT

Knowledge of global C cycle implications from changes to fire regime and climate are of growing importance. Studies on the role of the fire regime in combination with climate change on soil C pools are lacking. We used Bayesian modelling to estimate the soil % total C (% C_{Tot}) and % recalcitrant pyrogenic C (% RPC) from field samples collected using a stratified sampling approach. These observations were derived from the following scenarios: 1. Three fire frequencies across three distinctive climate regions in a homogeneous dry sclerophyll forest in south-eastern Australia over four decades. 2. The effects of different fire intensity combinations from successive wildfires. We found climate had a stronger effect than fire frequency on the size of the estimated mineral soil C pool. The largest soil C pool was estimated to occur under a wet and cold (WC) climate, via presumed effects of high precipitation, an adequate growing season temperature (i.e. resulting in relatively high NPP) and winter conditions sufficiently cold to retard seasonal soil respiration rates. The smallest soil C pool was estimated in forests with lower precipitation but warmer mean annual temperature (MAT). The lower precipitation and higher temperature was likely to have retarded NPP and litter decomposition rates but may have had little effect on relative soil respiration. Small effects associated with fire frequency were found, but both their magnitude and direction were climate dependent. There was an increase in soil C associated with a low intensity fire being followed by a high intensity fire. For both fire frequency and intensity the response of % RPC mirrored that of % C_{Tot}: i.e. it was effectively a constant across all combinations of climate and fire regimes sampled.

1. Introduction

Fires have major, immediate and longer-term effects on the turnover and make-up of organic carbon (C) via heating and consumption of

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biomass and the redistribution of residual, oxidised solids and gasses into the atmosphere and soil. There is fossil evidence of vegetation fires dating back to the Silurian (ca. 420 Mya), a time when vegetation cover and atmospheric oxygen concentrations became sufficient to sustain combustion (Glasspool et al., 2004; Jones and Chaloner, 1991). Rapid oxidation of organic matter (living and dead) facilitated by fire can release gasses directly to the atmosphere while the fate of non-gaseous pyrogenic products is more variable (Lal, 2013; Mouillot et al., 2006). This is determined by the composition and size of non-gaseous products, coupled with the timing and strength of dispersal forces applied to them (Santín et al., 2016; Lal, 2013). In some forests, very little soil organic matter (SOM) is directly altered by fire, as heating in soils under moving fires is limited to the near surface (i.e. 0 to 5 cm depth) (Mondal and Sukumar, 2014; Bradstock and Auld, 1995; Raison et al., 1986). The degree of consumption of the overlying humus is determined by its moisture content and the intensity of fire at the time, both of these factors being partially driven by weather (Santín et al., 2016; Boby et al., 2010; Bradstock et al., 2010). Fires leave a spectrum of biologically fixed C in the landscape ranging from living plant tissue to fully charred material and soots.

The portion of biologically fixed C in the post-fire landscape consisting of partially to fully charred plant tissue and soots, is termed pyrogenic carbon, PyC (Jenkins et al., 2016). Substantial research effort has been expended on the perceived C sequestration potential of PyC associated with its assumed recalcitrance (Baldock et al., 2013; Krull et al., 2003; Skjemstad et al., 1998). PyC recalcitrance can be strong, with observed persistence for centenial and millenial timescales, but is dependent on formation at high temperatures (>750 °C) from coarse, lignified fuels (Bird et al., 2015; Bodí et al., 2014; Hammes et al., 2007). Decomposition rates in chars formed at lower temperatures (<450 °C) or from fine material (low lignin content) may have weaker recalcitrance, which in some cases may be similar to other SOM particles of the same dimensions (Norwood et al., 2013; Knicker, 2011; Hammes et al., 2007). The recalcitrance of all SOM, including PyC, is enhanced when incorporated into the mineral soil where it is shielded from oxidation and other chemically degrading processes associated with fire (Santín et al., 2016). It has been argued that this physical protection by location in the soil is potentially more important to C mean residence time than the chemical recalcitrance of the specific SOM under consideration (Lal, 2013).

In natural forests, woodlands and shrublands, estimates of mineral soil C pools can exceed the aboveground amount, emphasising its importance in the global C cycle (Santín and Doerr, 2016; Vargas et al., 2008; Beringer et al., 2007). Despite the potential importance of soil pools of C, little is known about the way these pools may respond to variations in fire regimes (i.e. the frequency, intensity and season of fires) (Keeley et al., 2012). Such knowledge is important given that many forests in differing parts of the world are fire-prone (Archibald et al., 2013; Keeley et al., 2012), and that future changes in fire regimes are predicted (Clarke et al., 2011; Flannigan et al., 2009). A fundamental understanding of how soil C pools are affected by fire regimes is needed to predict their long-term fate given anthropogenic global change.

This study is an examination of how variations in recent fire regimes in fire-prone *Eucalyptus* dominated forests, in south-eastern Australia, have affected soil pools of C and recalcitrant pyrogenic C (RPC; the most recalcitrant fraction of PyC). This study also examines how such fire regime effects may be amended by regional-scale variations in temperature and rainfall within a homogenous forest type. Climatic models suggest that temperatures are likely to increase across eucalypt dominated forests, with possible increases or decreases in precipitation at a local level (CSIRO and Bureau of Meteorology, 2015; Clarke et al., 2013; Clarke et al., 2011). Such shifts have the potential to change net primary productivity (NPP), fire-proneness of the vegetation through floristic shifts and the incidence of severe fire weather in the landscape (Bradstock et al., 2014; Flannigan et al., 2009; Roxburgh et al., 2005). This study was designed to provide some integrated insight into the way that changes to fire regimes and climate may affect: i) soil C pools generally; and ii) the ability to enhance long-term C sequestration in soils through manipulation of the fire regime using planned burning. For example, Adams (2013) and Volkova and Weston (2015) have proposed that planned burning could be used to enhance soil pools of PyC, though the evidence for appreciable inputs from such fires is equivocal (Jenkins et al., 2016).

This study focussed on the fire frequency and sequential fire intensity aspects of the fire regime. Given evidence that C pools in the soil may vary as a function of time since fire (Sawyer et al., 2018) the study design held this effect constant by sampling only sites burnt 10 to 12 years previously. Over this time since fire interval, soil C pools were found to be stable after both unplanned and planned fires (Sawyer et al., 2018). The study was carried out across the Sydney Basin Bioregion, which is dominated by fire-prone eucalypt forests. Variations in fire frequency created by both unplanned and planned fires were used to explore effects on soil C pools at sites distributed across rainfall and temperature gradients. Remotely sensed estimates of fire severity (estimated damage to vegetation from fire) were used as a proxy of fire intensity in the sampling design.

The study therefore aimed to estimate how fire frequency and intensity combinations affected the distribution of total C and RPC in mineral soils across regional-scale variations in climate (i.e. mean annual precipitation and temperature).

2. Methods

2.1. Study sites

The study was carried out in the Sydney Basin Bioregion in south-eastern Australia (Fig. 1). The dissected landscapes of this Bioregion are dominated by sedimentary geology of mainly Permian/Triassic origins that result in predominantly acidic (e.g. pH 4 to 4.5), shallow (ca. 20 to 30 cm), sandy soils. Climate is cool-warm temperate with aseasonal rainfall. Vegetation is predominantly open forest and woodland (i.e. dry sclerophyll forest (DSF), (Keith, 2004)), dominated by *Eucalyptus*, *Corymbia* and *Angophora* spp., with an understorey often rich in sclerophyllous shrub species, graminoids and sedges (Keith, 2004). The region is fire-prone with an average interval of 15 to 20 years between fires (Bradstock et al., 2012).

The sites sampled for this study were a subset of those originally established to examine vegetation responses to climatic and fire regime gradients across the Bioregion (Hammill et al., 2016). Areas in several parts of the Bioregion characterized by contrasting combinations of mean annual precipitation (MAP) and mean annual temperature (MAT), were initially identified, in order to test the effects of variations in rainfall and temperature on soil C. Two areas with MAP of 1200 mm and contrasting MATs (12 °C, 16 °C) were classified as wet and cold (WC) and wet and warm (WW) respectively. A third area, with MAP of 1000 mm and MAT of 16 °C, was classified as intermediate and warm (IW) (Fig. 1). Study sites were then selected within these climatically differentiated areas (hereafter referred to as climatic regions) based on fire regime attributes (i.e. fire frequency and fire intensity) in order to test effects of fire regimes on soil C.

Three levels of fire frequency (FF; one, two or four fires between 1972 and 2003) were selected for each combination of MAT and MAP. These selections were based on mapped fire records since 1972 (New South Wales Office of Environment and Heritage unpublished data). Three replicate sites for each combination of MAT, MAP and FF class were sampled. All sites were situated in areas last burnt in the 2001/2002 or 2002/2003 peak fire seasons (i.e. likelihood of similar intensity). Sampling was conducted over a 2.5 year period (2011−2013), therefore equating to a time since fire range of 10–12 years. We assumed there were no major biases in fire regimes among the study sites prior to 1972.