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Evaluating long-term effects of prescribed fire regimes on carbon stocks in a temperate eucalypt forest

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ABSTRACT

Prescribed fires are a common management practice in the temperate forests of Australia, but effects on total forest carbon (C) of long-term prescribed fire regimes, involving multiple repeat fires, remain under-examined. This study quantified C stocks in multiple pools after 27 years of a long-term prescribed fire experiment in a mixed-species eucalypt forest in south-eastern Australia. The experimental design included five replications of each of five treatments – a long-unburnt Control, plus a factorial combination of two fire frequencies (c. 3-yearly 'High', c. 10-yearly 'Low'), and two fire seasons (Spring, Autumn) – encompassing up to 7 low-intensity repeat fires over the 27 years.

Overall, total C stocks (the sum of all pools: Above-ground biomass, Dead wood, Litter, and Soil) were significantly greater in Control than Fire treatments. Mean total C stock differences (Control minus Fire) were 36 Mg ha^{-1}, and increased with both fire frequency (46 Mg ha^{-1}, Control versus High frequency treatments) and fires in autumn rather than spring (42 Mg ha^{-1}, Control versus Autumn treatments). Mean differences had wide 95% confidence intervals (e.g. 4–67 Mg C ha^{-1}, Control versus Fire), indicating considerable uncertainty about the magnitude of effects of prescribed fire regimes on total C in these native forests. Weighted averaging of linear multiple regression models was used to identify the most important variables for explaining proportional C stock differences ((Control–Fire)/Control), and involved consideration of 85 explanatory variables including measures of fire intensity, fire severity, fuel, pre- and post-fire rainfall, fire weather, and topography. The best regression model explained 80% of variation in total C stock differences between Control and Fire treatments. Consistently important explanatory variables were those representing or associated with fire intensity (flame angle, wind speed, Forest Fire Danger Index), and number of prescribed fires. Measures of fuel load, pre- and post-fire rainfall, and, in particular, fire severity, were less important explanatory variables. The study provides indications of management options for minimising C stock decreases associated with prescribed fire regimes in temperate eucalypt forests; notably, wide fire intervals (closer to 10 than 3 years), and utilising strategies to minimise mean fire intensity, including burning in moist (spring) rather than dry (autumn) conditions.

1. Introduction

Prescribed fire is seen as a primary management option to mitigate forest wildfire activity, and thereby reduce wildfire carbon emissions, both in Australia (Adams, 2013), and throughout the world (Narayan et al., 2007; Hurteau and North, 2009; Vilén and Fernandes, 2011; Clark et al., in press). However, the long-term potential for prescribed fires to mitigate carbon emissions from wildfires in temperate Australian forests is contested, on the basis that predicted 'outlays' of carbon emissions produced by extensive use of prescribed fires could equal or exceed emissions 'savings' through decreased wildfire intensity and extent (Bradstock et al., 2012). More detailed evaluations of the carbon trade-offs associated with prescribed fires will require accurate quantification of prescribed fire effects on forest carbon stocks, but such data are currently lacking for temperate Australia (Adams, 2013).

Fire mediates carbon emissions through multiple processes including combustion, decomposition and respiration, transfers between pools (e.g. live to dead), and post-fire regeneration (Williams et al., 2012a). As such, full evaluation of prescribed fire effects on forest carbon depends on integrated assessments of

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carbon stocks in multiple pools, namely, Above- and Below-ground biomass, Deadwood, Litter, and Soil organic matter (IPCC, 2003). In addition, evaluations of long-term carbon trade-offs associated with prescribed fires will need to go beyond effects of single fires to consider the cumulative effects of multiple repeat fires, that is, of prescribed fire regimes. To date, just one study has assessed the effects of single prescribed fires on carbon stocks in multiple pools of an Australian temperate eucalypt forest (Volkova and Weston, 2013), and none have evaluated the longer-term effects on multiple stocks of prescribed fire regimes, including multiple fires that encompass a range of burning conditions.

In general, effects of fire regimes on forest carbon stocks will depend on the intensity and associated severity of individual fires, and on the intervals between fires. Here, fire intensity involves measures of energy release (e.g. fireline intensity, temperature, residence time; Keeley, 2009), whereas fire severity is a result of interactions between fire intensity and the ecosystem, and involves measurable impacts of fire on system components (e.g. fuel consumed, crown volume scorched; Keeley, 2009; Kasischke et al., 2013). The two are correlated, so that increasing fire intensity is usually associated with increasing severity (Keeley, 2009), and with greater impacts including increased combustion losses, tree mortality, post-fire regeneration, and soil erosion in Australian ecosystems (Williams et al., 2012a). Fire intensity and severity are often greater under dry conditions (Chatto and Tolhurst, 2004; van Mantgem et al., 2013), and thus will be influenced by the timing of burning during the fire season (Knapp et al., 2005). In addition, the interval between fires will influence the amount of fuel available to burn, as well as the nature of that fuel in the form of vegetation composition and structure (Williams et al., 2012a).

Accurately predicting effects of fire regimes on forest carbon stocks is often difficult because a 'multitude of factors' (Keeley et al., 2008) influence fire intensity and severity, and influence post-fire recovery. Fire severity is affected both by abiotic factors like aspect and slope (Keeley et al., 2005), and pre-fire climate (van Mantgem et al., 2013), and by biotic factors particularly fuel load and fuel moisture (Pausas and Paula, 2012; Switzer et al., 2012). Abiotic factors like topography and climate will also influence ecosystem responses, and thus carbon stock changes, in the post-fire environment (Keeley, 2009). For example, the degree and duration of changes in soil carbon stocks will vary with fire severity, but also with post-fire interactions between climate and topography, which influence erosional losses and plant inputs to soil through regeneration and growth (Certini, 2005). Similarly, fire effects on tree growth will depend on the immediate damage to roots, stems and crown (Kellas et al., 1984; Murphy et al., 2010), and on the post-fire growth environment including climate and stand structure (Hurteau and North, 2009; Bennett et al., 2013). Teasing apart these various influences to identify the most important variables for explaining fire effects on forest carbon stocks, will not only improve mechanistic understanding but will also help with identifying fire management options; that is, can carbon stock changes associated with prescribed fire be consistently linked to particular variables, and do these insights offer opportunities to actively manage the carbon 'outlays' (Bradstock et al., 2012) of prescribed fire regimes?

This study examines the long-term effects of prescribed fire regimes on multiple carbon pools in a mixed species eucalypt forest in Victoria, south-eastern Australia. Forests of this type contain the majority of Victoria's forest carbon due to their moderate productivity and extensive distribution (Kaye, 2009), and are likely to be regularly burnt as part of an expanded prescribed fire program that aims to reduce wildfire risks (Parliament of Victoria, 2010). The experimental design includes four prescribed fire treatments, as a factorial combination of two fire seasons and two fire frequencies, involving 2–7 low-intensity fires over 27 years. Previous papers have examined the effects of these prescribed fire treatments on tree growth and standing tree-based carbon stocks (Bennett et al., 2013), and on the nature and stocks of coarse woody debris (Aponte et al., in press). This paper combines the tree and coarse woody debris carbon stock data with coincident measures of carbon stocks in Soil and Litter, to present a synthesised analysis of long-term prescribed fire effects on multiple carbon pools. By quantifying carbon stocks in multiple pools after 27 years of prescribed fire treatment, our aim was to improve the empirical knowledge base for assessing long-term carbon stock changes associated with prescribed fire regimes in temperate eucalypt forests. In addition, using multivariate analyses of a range of fire, fuel, climate and topographic variables, we aimed to identify the most important variables for explaining these changes, with a view to informing options in prescribed fire management.

2. Material and methods

2.1. Study design

The study involved replication of prescribed fire treatments in native eucalypt forest at five locations within a 25 km radius in the Wombat State Forest, Victoria, south-eastern Australia (37°27′S, 144°17′E). Study details, including environmental and stand characteristics of each location, are provided in Bennett et al. (2013). Briefly, the study area straddles the Great Divide, at elevations 590–760 m above sea level, on an underlying geology of Ordovician sedimentary rock. Soils are 'stony earths' or 'friable earths, mottled duplex soils' (Rowan et al., 2000), which are classified as Kandosols and Dermosols in the Australian Soil Classification (ASRIS, 2011). The climate is temperate (annual rainfall 800–900 mm), and the predominant forest is 'Open Forest' (Specht, 1981) dominated by mixed eucalypts (*Eucalyptus obliqua* L'Her., *E. radiata* Sieber ex DC., *E. rubida* H. Deane and Maiden) of mean height 26 m, and under-bark basal area 30–40 $m^2\ ha^{-1}$ (Bennett et al., 2013). The understorey consists of a discontinuous ground layer of Austral bracken (*Pteridium esculentum* (G. Forst) Cockayne) with native perennial grasses, forbs and rushes, beneath a sparse shrub layer to 2–4 m height (Tolhurst, 2003).

The study used a randomised block design of five treatments randomly allocated within each of the five locations (25 treatment areas, 3–35 ha; Tolhurst and Flinn, 1992). These locations were chosen on the basis that they encompassed the structural range of Open Forest within the region, they had not been burnt for at least a decade before the start of the experiment, and that they each contained relatively uniform vegetation that could be divided into five treatment areas of at least 3 ha (Tolhurst and Flinn, 1992). The five treatments were a long-unburnt Control, plus a factorial combination of two prescribed fire frequencies (approximately every 3 years 'High', or every 10 years 'Low'), and two prescribed fire seasons (October/November 'Spring', or March/April 'Autumn'). The first prescribed fires were in 1985–1987, and the number of prescribed fires over the study period ranged from 2 to 3 in Low frequency treatments, and 4 to 7 in High frequency treatments (Bennett et al., 2013). Time since last known wildfire to the start of the carbon stock measures in late 2011 was 37–80 years, and time since last prescribed fire was 4–8 years in Low frequency treatments, and 3–6 years in High frequency treatments (Bennett et al., 2013). All prescribed fires were considered low intensity (Tolhurst and Flinn, 1992; DSE, 2003), and field observations indicated no significant difference among treatments in mean measures of fire intensity (Table 1). However, some measures of mean fire severity were significantly greater for Low than High frequency fire treatments (e.g. mean and maximum scorch height;