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Decreases in standing tree-based carbon stocks associated with repeated prescribed fires in a temperate mixed-species eucalypt forest

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ABSTRACT

Prescribed fire is a common management practice in fire-tolerant forests, and one that has potential carbon costs. Previous assessments of the carbon costs of prescribed fire regimes in temperate Australia have been based on little empirical data, and have focused on direct fire effects (area burnt, fuel consumed) but have largely ignored potentially substantive indirect effects on tree mortality and growth. This study measures effects of four prescribed fire treatments on standing tree-based carbon stocks, and on individual tree growth and mortality, in a fire-tolerant eucalypt forest of south-eastern Australia. Prescribed fire treatments were as a factorial combination of two seasons (autumn or spring) and two frequencies (3-yearly 'High', or 10-yearly 'Low'), were replicated over five study areas, and involved 2–7 low-intensity fires over 27 years.

Total standing tree-based carbon stocks (live and dead) were significantly less in prescribed fire than control treatments. However, the mean carbon difference (25 Mg ha^{-1}) had a wide 95% confidence interval (2–48 Mg ha^{-1}), indicating a high degree of uncertainty about the magnitude of prescribed fire effects in these native forests. Overall decreases were consistent with detection of both direct and indirect effects of prescribed fire treatments. Direct combustion effects on bark were minimal (c. 0.2–0.4 Mg ha^{-1}), but were also indicated by significantly less carbon in dead large stems in fire than control treatments despite evidence of marginally increased mortality of individual large stems in the former. Indirect effects of repeated prescribed fires were also detected as significantly decreased mean annual diameter increment of individual large *Eucalyptus obliqua* over 27 years (particularly of stems 20–50 cm diameter). With respect to prescribed fire type, small live stem densities and associated carbon stocks were greater in autumn than spring, and in Low than High frequency treatments, and carbon stocks in large dead stems were greater in High than Low frequency treatments. This suggested that c. 10-yearly fires in autumn provided the most scope for maintaining future capacity to fix carbon. Nonetheless, decreases in total standing tree-based carbon stocks were not significantly different among prescribed fire treatments, suggesting tree-based carbon stocks were more influenced by prescribed fire *per se* than by fire season or frequency.

1. Introduction

Prescribed fire, the planned or 'deliberate introduction of fire under specified fuel and weather conditions' (Burrows et al., 2010), has been regularly used in forest management throughout Australia and elsewhere to maintain or restore species and habitat, to enhance post-logging recovery, and to reduce fuel loads and associated wildfire hazards (Fernandes and Botelho, 2003; Carter and Darwin Foster, 2004; Burrows et al., 2010; Penman et al., 2011). In particular, the potential for prescribed fire to reduce risks from (unplanned) wildfire is highly topical given ongoing experiences of large damaging wildfires (Adams, 2013; San-Miguel-Ayanz et al., 2013), and given recent predictions of more frequent, extensive and severe wildfires under climate change both in temperate Australia (Bradstock, 2010; Clarke et al., 2011; King et al., 2013), and globally (Flannigan et al., 2013). In south-eastern Australia, this has led to implementation of recommendations for an expanded prescribed fire program (Parliament of Victoria, 2010; DSE, 2012), potentially involving hundreds of thousands of hectares of State land each year, and comparable with historical peaks in annual burnt area (Attiwill and Adams, 2008).

Since forest fires emit greenhouse gases, regular burning of large areas of forest by prescribed fire will likely have a carbon cost

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(North and Hurteau, 2011). However, this cost might be acceptably minor if the 'outlay' of carbon emissions from prescribed fires was offset by a 'return on investment' of decreased overall emissions from wildfires (Bradstock and Williams, 2009). In North America and Europe, various studies have indicated considerable potential for carbon emission mitigation using prescribed fires (Narayan et al., 2007; Hurteau and North, 2009; Vilén and Fernandes, 2011; Ghimire et al., 2012), while others have found this potential to be limited (Campbell et al., 2011). Similarly, in temperate Australia, while some see considerable opportunities for prescribed fire to mitigate wildfire impacts on forest carbon (Adams, 2013), others have found minimal opportunity (Bradstock et al., 2012).

Previous assessments of the relative carbon costs of prescribed fire regimes in temperate Australia have focused on the direct effects of burning (area burned, fuels consumed; e.g. Bradstock et al., 2012). However, research elsewhere suggests that the immediate direct effects of fire account for only a portion of actual forest carbon losses (Hurteau and North, 2009). In particular, indirect effects on stand structure and growth through scorch and death of trees and understorey plants (Busse et al., 2000; Peterson and Reich, 2001; van Mantgem et al., 2011), and associated decomposition of fire-killed biomass (Ghimire et al., 2012), can result in a sustained 'carbon uptake legacy' that varies with fire severity (Ghimire et al., 2012). Thus, understanding the longer-term legacies of prescribed fire on tree growth and tree-based carbons stocks is key to assessing the full carbon 'outlays' of different fire regimes. Indeed, Campbell et al. (2011) argue that 'only when [fuel-reduction] treatments change the equilibrium between growth and mortality can they alter long-term carbon storage'.

Data to underpin long-term assessments of prescribed fire effects on forest carbon are currently lacking for temperate Australia. Few studies have examined effects of prescribed fire on forest carbon stocks in these forests, and even fewer have considered impacts of multiple prescribed fires, or after fires of contrasting season and/or frequency. In addition, research of prescribed fire effects on tree mortality and growth in fire-tolerant forests of Australia has thus far been limited to small treatment plots of minimal replication in sub-tropical (Guinto et al., 1999) or in south-western Australia (Burrows et al., 2010).

This paper presents findings from one of the most detailed and long-term studies of prescribed fire in Australia (Adams and Attiwill, 2011). We use field measurements to examine effects of prescribed fire regimes on (standing) tree-based carbon stocks, and on long-term tree growth and mortality, in an extensive forest type of south-eastern Australia dominated by fire-tolerant eucalypts. The study has a number of unique attributes, including: (1) four prescribed fire treatments as a factorial combination of two fire seasons and two fire frequencies; (2) assessment of carbon stocks after 26 years of known prescribed fire treatment, encompassing 2–7 repeat fires; and (3) repeated measures of individual tree growth over 27 years.

Our focus is carbon in standing trees because this is the predominate biomass carbon pool in Australia's temperate eucalypt forests (Norris et al., 2010; Volkova and Weston, 2013), and is likely to be the largest carbon pool impacted by management practices like prescribed fire (Moroni, 2012). Estimates of carbon pools in forests comparable to ours have thus far been based on very few samples, with stocks in live standing trees expected to be in the range 120–240 Mg ha^{-1} (Grierson et al., 1992; Volkova and Weston, 2013). We anticipate that carbon stocks in the soil (a focus of our ongoing research) will be appreciable but less than those in aboveground components (c. 80 Mg ha^{-1} to 30 cm depth; Volkova and Weston, 2013), and that stocks in the understorey vegetation of our study sites will be negligible given a non-existent shrub layer. Similarly, based on Volkova and Weston (2013), we anticipate that stocks in dead standing trees (c. 9 Mg ha^{-1}) and in fallen timber ('coarse woody debris'; c. 15 Mg ha^{-1}) will be relatively minor, and each less than 10% of stocks in live standing trees.

The paper's primary aim was to improve the empirical knowledge base for assessing and predicting effects of prescribed fire regimes on standing tree-based carbon stocks. The study's null hypotheses were: (1) no effect of prescribed fire treatments on tree mortality or growth; (2) no effect of prescribed fire treatments on standing tree-based carbon stocks; and (3) no effect of prescribed fire season or frequency on standing tree-based carbon stocks.

2. Materials and methods

2.1. Study areas

The study included five areas (known locally as the 'Fire Effects Study Areas', FESA) within a 25 km radius in the Wombat State For-

Table 1
Summary of the environment, stand characteristics, and fire history of the five study areas in central Victoria, Australia.

	Area				
	Blakeville	Barkstead	Musk Creek	Burnt Bridge	Kangaroo Creek
Latitude/Longitude	37°31′S, 144°10′E	37°29′S, 144°05′E	37°28′S, 144°10′E	37°25′S, 144°20′E	37°19′S, 144°18′E
Elevation (m, above sea level) [a]	590–665	635–650	620–720	710–760	615–645
Slope (°) [a]	1–13	0–4	1–16	0–15	0–21
Aspect (°) [a]	130–295	120–315	40–310	30–270	0–340
Mean annual rainfall (mm) [b]	871	901	856	896	814
Mean monthly max temp. (°) [b]	9–24	8–23	10–24	7–22	8–24
Mean monthly min temp. (°) [b]	2–10	2–10	3–11	2–11	3–12
Tree mean basal area (m^2/ha) [c]	43	31	29	43	42
Tree mean height (m) [c]	26	28	25	26	23
Last thinning [d]	1964	1979	1974	1977	1975
Last wildfire [d]	1935	1931	1974	1953	1944
Total experimental area (ha) [d]	81	19	78	62	128
Mean fire interval (yrs): AH [e]	3.0 (6, 1987–2007)	4.0 (5, 1987–2007)	4.0 (6, 1987–2008)	5.7 (4, 1987–2007)	3.4 (6, 1987–2009)
Mean fire interval (yrs): AL [e]	9.5 (3, 1987–2008)	9.0 (3, 1987–2007)	16.0 (2, 1987–2004)	16.0 (2, 1987–2004)	9.0 (3, 1987–2007)
Mean fire interval (yrs): SH [e]	3.6 (6, 1985–2008)	3.6 (6, 1985–2005)	2.7 (6, 1986–2005)	2.7 (7, 1986–2008)	2.8 (7, 1985–2008)
Mean fire interval (yrs): SL [e]	9.0 (3, 1985–2005)	9.0 (3, 1985–2005)	8.5 (3, 1986–2005)	8.5 (3, 1986–2005)	9.0 (3, 1985–2005)

[a] Range from this study's measurement plots.
[b] From automated weather station within 4 km of each area (1986–1999 for Barkstead, 1986–2002 plus 2007–2010 for all others).
[c] Based on measures of large stems (diameter over-bark ⩾ 20 cm at 1.3 m height) in this study's three plots per control treatment; basal area is under-bark.
[d] Tolhurst and Flinn, 1992.
[e] Mean interval in years between successive prescribed fires during the experimental period (values in brackets indicate the number of prescribed fires, and the years of first and last prescribed fires); treatment abbreviations: 'AH' autumn High frequency, 'AL' autumn Low frequency, 'SH' spring High frequency, 'SL' spring Low frequency.