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Indirect effects of climate change on forest structure alters fuel availability in wet Eucalypt forests

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Abstract

The direct effects of climate change are increasing the frequency of high-intensity fire events in many ecosystems across the globe, including wet Eucalypt forests of south-eastern (SE) Australia. Recurrent high-intensity fire can alter vegetation structure and composition, and the resultant alternative vegetation states may be more likely (positive feedback) or less likely (negative feedback) to burn again compared to the vegetation community replaced. These indirect effects of climate change have been reported for a range of different ecosystems across the globe. However, a common limitation to many empirical studies is the narrow temporal range of observations, often limited to a single fire season. In turn, this limits our understanding of the potential for vegetation-mediated indirect effects of climate change to generate positive or negative fire feedbacks across the range of climate conditions common to the region.

In wet Eucalypt forests of SE Australia, dead fuel moisture content (FMC) is a key determinant of fire activity and is therefore a useful metric on which to quantify the potential for feedbacks across alternative forest states. To quantify potential for indirect effects of climate change to alter future fire activity, FMC was modelled in the open and at seven alternative forest states to wet Eucalypt forest using a process-based FMC model. The model was run using a long-term climate dataset (1973 – 2020), which were transferred from macro- to microclimate values using forest structural properties derived from lidar. Hourly FMC outputs were summarised to fuel availability (FMC < 16% for at least one hour each day) to understand the potential for positive, negative of no feedbacks on potential fire activity.

The results showed that mean annual FMC was significantly different between alternative forest states across each of the 48 years of climate data – which act as independent replicates for different climate conditions in our experimental design. By quantifying these differences using the metric of fuel availability, we have demonstrated that statistically significant differences in FMC translate into meaningful differences in the context of potential fire activity. Overall, the results show strong positive and negative feedbacks across the alternative forest states compared to the mature wet Eucalypt forest that they replaced, which were greater than age-related differences within the wet Eucalypt forest sites. Overall, our results support the hypothesis that indirect effects of climate change, acting through vegetation conversion to alternative forest states, have a substantial impact on the potential for future fire activity, with important implications for land and fire managers in this region.

1. Introduction

Fire is a critical process in many ecosystems globally that influences the distribution, composition, and successional stage of vegetation communities (Pausas et al., 2017). While fire is important for the maintenance of many ecosystems, altered fire regimes can have negative impacts (Enright et al., 2015). Climate warming is elevating fire danger in many locations across the globe (Abatzoglou et al., 2019; Flannigan et al., 2000; Jolly et al., 2015) and increasing temperatures coinciding with more variable rainfall are expected to increase fire frequency in south-eastern (SE) Australia (Harris and Lucas, 2019). Repeated high-intensity fires can alter the successional pathways of forest communities by overwhelming the utility of fire adaptive traits (Fairman et al., 2019), which can lead to abrupt shifts in ecosystem composition and forest structural properties (Bowman et al., 2014), in conjunction with an overall shift to forests of a lower age class. This may indirectly affect future fire activity if younger, or alternative forest states create microclimate conditions conducive to increased fire activity (Enright et al., 2015). This phenomenon is commonly referred to as fire-vegetation feedbacks, which can be positive or negative. Positive feedbacks relate to vegetation conditions likely to increase fire activity, while negative feedbacks include vegetation states likely to reduce potential fire activity (Tepley et al., 2018). Positive and negative fire-vegetation feedbacks have been reported across a range of different ecosystems, including in wet Eucalypt forests of SE Australia (Burton et al. 2019). However, a key limitation of these studies is the relatively narrow temporal range of observations – typically one or two seasons, which in turn limits our understanding of the potential for alternative forest states to generate positive or negative feedbacks across the range of climate conditions that are characteristic to the region.

Forests in productive regions can support high biomass loads that reaccumulate quickly after disturbance, so they almost always have enough fuel to sustain large fires (Cawson et al., 2018). Consequently, in these forests it is primarily the fuel moisture content (FMC) that limits fire activity, which is therefore a useful metric for understanding the potential for positive or negative feedbacks. Recurrent high-intensity fires in the dominant mature *Eucalyptus regnans* forests in this region have caused some areas to shift to alternative forest types, that are potentially more adapted to the novel short-interval fire regime (Fairman et al., 2016).

Field studies across a range of alternative forest states and age classes to mature wet Eucalypt forests (Brown et al., 2021; Burton et al., 2019) report both positive and negative feedbacks. However, a key limitation to these studies is that they have a limited timeframe of observation. Consequently, it is difficult to determine whether the feedbacks reported are due to the indirect effects of climate change on vegetation structure and composition, or more strongly related to the specific climate conditions throughout the period of observation. Given these limitations, and the variability in weather and climate conditions in SE Australia (Harris et al., 2019), modelling the potential for fire vegetation feedbacks across alternative forest states across the full range of climate conditions characteristic to the region would enhance our understanding of the potential for indirect effects of climate change to influence future fire activity.

Therefore, the aim of this study is to explore whether observed differences in dead FMC resulting from vegetation-mediated effects of climate change are replicated across the range of climate conditions experienced in the region, and, to evaluate the impact of this on potential fire activity.

2. Methods

To understand the potential for indirect effects of climate change (through changes to forest structure and composition) to influence future fire activity, dead FMC was modelled across seven alternative forest state field sites, and one above canopy open weather station (Figure 1). Dead FMC (represented by automated fuel moisture sticks) was modelled for 48 years using a calibrated process-based model (van der Kamp et al., 2017) that was driven by reconstructed climate data transferred to microclimate values (Brown et al., 2016; Jeffrey et al., 2001). The seven sites cover a range of alternative forest state sites to mature *Eucalyptus regnans* forests in SE Australia (which is assumed to be analogous to 80-year-old *E. regnans* in this study).

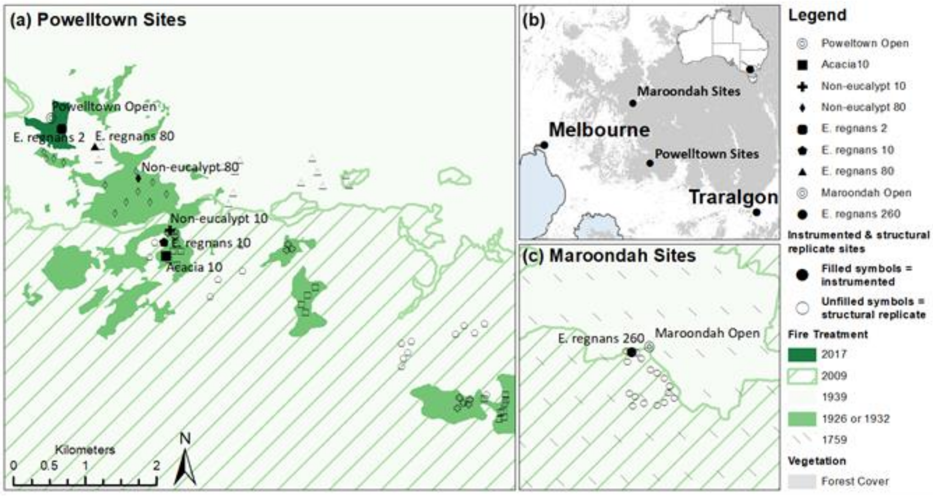

Figure 1. Location of the study areas, including seven instrumented field sites and two open (control) weather stations within the Central Highlands, Victoria, in SE Australia (b). Coloured and dashed areas indicate the fire disturbance conditions, denoting the most recent fires affecting forest structure at the alternative state forest sites. The 1939 fire (light green) affected the entire Powelltown (a) and Maroondah (c) regions.

Table 1. Site information for the open station and seven alternative forest states to wet Eucalypt forest used in this study; including four Eucalypt-dominated sites, one Acacia dealbata site, and two sites dominated by (typically) understorey species (Non-eucalypt).

Site name	Age	Rainfall (mm y^{-1})	Aspect (°)	Elevation (m)
Powelltown Open	-	1495	267	740
Acacia_{10}	10	1322	134	558
Non-eucalypt_{10}	10	1344	128	606
Non-eucalypt_{80}	80	1402	166	635
E. regnans$_{2}$	2	1481	153	735
E. regnans$_{10}$	10	1337	142	588
E. regnans$_{80}$	80	1448	204	672
E. regnans$_{260}$	260	1297	156	727

Hourly FMC data were summarised to mean annual FMC and a simple one-way analysis of variance (ANOVA) and Tukey's Honest Significant Difference (HSD) post-hoc test were conducted to detect statistically significant differences. To understand the importance of differences in FMC in the context of potential fire activity, fuel availability (FA) was assessed following Cawson et al. (2017), where fuels were considered available to burn on a given day if the site minimum modelled FMC is below 16% for at least one hour of that day.

3. Results

FMC modelled at the hourly scale (n=420 767) were summarised at a high level to mean annual FMC (n=48) for each alternative forest state. At this scale, there were significant differences in mean annual FMC ($F_{7,326}$ = 1307.2, $p < 0.001$), with a subsequent post-hoc test between group (alternative forest state) means finding significant differences across all groups at the $p < 0.05$ level. Substantial differences in FA were modelled across the alternative forest states compared to the mature wet Eucalypt forest they replaced. Mean annual days of fuel availability at *E. regnans*$_{80}$ ranged from 0 (1992, 1996, 2011) to 24 days (1976), with 19 days of FA in 2009 – the year of the 'Black Saturday' fires in Victoria, Australia. FA was consistently higher (lower FMC) at Acacia_{10} and Non-eucalypt_{10} compared to *E. regnans*$_{80}$, peaking at 242 days (1974) at Non-eucalypt_{10} (Figure 2). In contrast, between 1973 and 2020, FMC did not fall below 16% at the Non-eucalypt_{80} site, while FA of only 2 days was modelled at the *E. regnans*$_{2}$ site (1974 and 2009). Modelled FA at the regenerating (*E. regnans*$_{10}$) and multi-cohort (*E. regnans*$_{260}$) were similar to *E. regnans*$_{80}$, with both sites recording years with zero days of fuel availability, and peak years of 16 and 32 days, respectively.

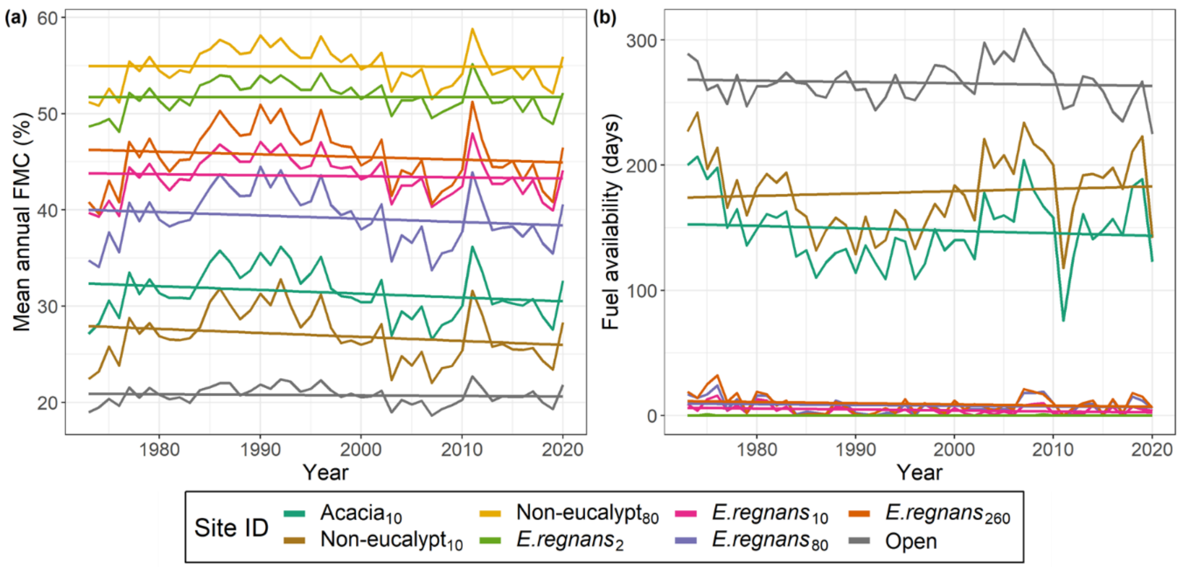

Figure 2. Modelled mean annual fuel moisture content (a) and fuel availability (b) for the alternative forest states between 1973 and 2020. The regression line indicates a simple linear model smoothed across each year of the 48-year climate dataset.

4. Discussion

Our research suggests that the impact of vegetation-mediated indirect effects of climate change on potential fire activity across seven alternative forest states is substantial. Across 48 years of modelled climate data, the results were broadly consistent with single-season observations reported by Burton et al. (2019) and Brown et al. (2021), suggesting that these comparatively shorter studies captured an appropriate range of climatic conditions. Across the 48-years of modelled data, FMC variability within and between the alternative forest states was greater than modelled FMC variability at the open site, suggesting that the indirect effects of climate change (that have altered forest structure and composition) may be more important than the direct effects on FMC in this ecosystem.

Overall, age related differences in dead FMC within E. regnans states were weaker than differences across different alternative forest state vegetation associations, with important implications for land management. We found short-term, positive fire feedbacks related to FMC for non-eucalypt forests in this region, which, as the forest ages, become negative feedbacks. In contrast, our results did not support the existence of positive fire feedbacks related to FMC across different ages of E. regnans forest. Consequently, our findings suggests that the maintenance of a Eucalypt-dominated canopy layer, potentially with patches of older non-eucalypt type forests will provide the most robust vegetation-state related buffer to future fire activity in the Central Highlands regions of SE Australia. Wet Eucalypt forests in SE Australia are a highly valued and contested forest system, and our findings enhance our understanding of ways in which these systems may be vulnerable, or resilient, to future climate change.

5. Conclusion

The indirect effects of climate change, acting through changes to vegetation structure and function, have a significant impact on fuel availability across wet Eucalypt forests in SE Australia. Indirect climate change effects resulted in both positive and negative feedbacks for potential fire activity compared to mature wet Eucalypt forest. Regenerating alternative forest states exhibited strong positive feedbacks, that were consistent across modelled data and observations in the literature. In contrast, feedbacks at *E. regnans* forests between 10-260 years were limited, while juvenile (2-year-old) *E. regnans* forests, and older (80-year-old) alternative state forests exhibited negative vegetation fire feedbacks.

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