Topography not tenure controls extent of wildfire within Mountain Ash forests

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Abstract
Two high intensity wildfire events, 70 years apart, burnt large areas of Mountain Ash forests in the Central Highlands, Victoria, Australia. Both resulted in Royal Commissions (the strongest form of judicial inquiry in Australia) as to their cause(s) owing to large losses of life and property. Here we tested the hypothesis that site 'wetness'—determined using a Topographic Wetness Index—is a major determinant of the extent of fire (% of sample points that burnt) within high intensity wildfire events and across tenures. We show that wetness dominated the extent of fire in these forests in both the 1939 and 2009 wildfire events. Mountain Ash forests are now strongly skewed in their distribution, with wetter and older forests favored by protected tenures (e.g. National Parks) designed to meet needs for water and conservation. In 2009, the extent of fire at the stand scale in water catchments and conservation tenures was twice that in 1939. In land tenures with multiple uses (e.g. State Forests), the extent of fire was one-third less in 2009 than it was in 1939. Topographic controls on water availability, and major droughts, will likely continue to dominate the extent and likelihood of fire in these forests.

1. Introduction

Australian eucalypt forests have adapted to fire regimes for around 60 million years [1, 2] and rank amongst the most fire-prone worldwide. Wildfires (or bushfires) in eucalypt forests are commonplace and numerically, most fires are brought under control quickly with little or no loss of life or damage to assets. As with wildfires generally, the small proportion (≤5%) of fires that escape early suppression cause most of the losses of life and property and pose the biggest challenges to ecological sustainability [3, 4]. South-eastern and south-western Australian forests are especially well known for destructive bushfires, with Mountain Ash (Eucalyptus regnans F Muell.) forests the most dangerous.

Around $3 \times 10^6$ ha of forest in south-eastern Australia burnt in the decade from 2000 to 2010 [5], culminating in the Black Saturday fires of 2009 that were centered on the Mountain Ash forests (see also [6, 7]). The Black Saturday fires killed 173 people and were Australia’s worst civilian tragedy [5]. Seventy years earlier, the 1939 fires burnt nearly $2 \times 10^6$ ha over the course of several days, 71 people died and more than 650 dwellings and other structures were destroyed. At the time, the population of Victoria was <2 million (in 2009 it was 5.4 million) so the 1939 fires were arguably an even greater disaster. The social, economic and ecological significance of the 1939 and 2009 fires is underscored by the fact that both led to Royal Commissions [8, 9], the strongest form of judicial inquiry in Australia. Mountain Ash forests constituted significant proportions of both the 1939 and the 2009 wildfire events and accounted for much of the losses of life and property within their immediate vicinity.

Biologically, Mountain Ash is an iconic hardwood. Mature forests often reach heights of 80+ m, while some individual trees have been recorded as reaching 100+ m. In sheltered locations, mature trees can survive for several hundred years [2, 10]. Mountain Ash dominates more than 100 000 ha of tall-open forests in the Central Highlands, north-east of Melbourne, Australia, as well as significant areas in other
regions of Victoria and in Tasmania. This species and these forests are dependent on fire for regeneration [2, 7, 11] yet burn in bushfires of the greatest possible intensity, owing to their fuel loads that dry out during infrequent droughts accompanied by heatwaves.

Mountain Ash forests also represent a large proportion of water catchments that service Melbourne that were declared—and often fenced and closed to all other activity—from the late 19th century onwards [12]. Much of these catchment areas now have protected tenures. In addition to National Parks, other protected land tenures (see table 1) make up a large proportion of all Mountain Ash forests in Australia. Protected area tenure (e.g. National Parks) has been the primary conservation tool of governments of all persuasions in most western democracies for hundreds of years [13]. However, few if any studies have attempted to contrast the extent of major wildfires within adjacent protected and non-protected tenures.

We examined how terrain-driven variation in site moisture affected the proportion of Mountain Ash forest (at the stand scale) that burnt (extent of fire) in these two major fires. We base our quantitative analyses on readily determinable properties. We obtained land tenure and fire occurrence/mapping data from the Victorian Government. We used as our principal measure of water availability, a topographic wetness index (TWI), as previously defined by Beven and Kirkby [14]. Topographic indices have a 40+ year history of use and have been successfully used to predict broad distributions of eucalypts [15]. Similarly, TWIs have been extensively used in studies of the hydrology of Mountain Ash forests [16]. Our analysis is also, *inter alia*, a test of land tenure on fire extent/likelihood at the scale of our measurements. Our null hypotheses were that: (a) TWI would not be related to the extent of fire, and (b) the extent of fire would not be dependent on land tenure.

### 2. Methods

We first identified Mountain Ash forests as the ‘wet forest’ class within the area broadly defined as the Mountain Ash estate in the Central Highlands of Victoria (an area of ~10 000 km²), and as mapped by the Victorian Government. This estate encompasses numerous land tenures (see table 1) but most commonly: National Parks and Reserves; Melbourne water catchments (often overlapping with National Parks); State Forest, and other tenures. Information about catchment and land tenure boundaries was accessed through the Victorian Spatial Data Directory.

We estimated the probability of occurrence of Mountain Ash in relation to TWI and land tenure using binomial logistic regression modeling (incorporating generalized linear models), with the response being presence/absence of Mountain Ash forest (similar to the approach used by Wood et al [17]). We generated 100 000 random points within the Mountain Ash estate. For each random point we calculated a TWI as defined by Beven and Kirkby [14]. Topographic wetness indices based on digital elevation models are widely used [18] and predict equilibrium soil saturation broadly from analysis of the upslope contributing areas and local slope (e.g. [19]). We assessed upslope contributing areas and slopes using a 30 m resolution digital elevation model (Shuttle Radar Topography Mission derived DEM). Generalized linear models were selected since they can cope with non-normal type data and are widely used in spatial ecological data analysis. Each point was also classified according to its tenure as of 2009: (a) inside a declared water catchment and within a National Park or Reserve; (b) outside declared catchment areas but within a National Park or Reserve; (c) inside a declared catchment and within a State Forest; and (d) outside declared catchments but within a State Forest or other non-reserve tenure.

We then selected a separate set of 100 000 random points, this time limited to areas within the fire boundary. We used these points and their TWI to quantify the extent of fire in relation to wetness. Boundaries of fires in the Central Highlands, and the distribution of Mountain Ash therein (as mapped by the Victorian Government), are shown for both 1939 (figure 1(a)) and 2009.
Figure 1. Maps showing distribution of Mountain Ash (*E. regnans*) in the Central Highlands of Victoria in relation to land tenure and wildfires in (a) 1939 and (b) 2009. The red shaded area indicates the boundaries of fire-affected Mountain Ash and is the study area. Insets show location of study area in relation to overall fire extent. Note that the scale of the map precludes representation of unburnt areas within burnt areas.

(figure 1(b)). Also shown are the boundaries of the 1939 fires (total area approximately 3418 000 ha) and the 2009 fires (approximately 446 600 ha). We grouped TWI data into five nominal classes: TWI <3 = very dry; TWI 3–6 = dry; TWI 6–9 = medium; TWI 9–12 = wet; TWI >12 = very wet.

As a further assessment of the effects of tenure and moisture availability on fire extent, we used the same
two study areas selected independently by Taylor et al [20]. The two areas (or sub-regions) were close to Mount Disappointment (approximately 6000 ha) and on the plateau encompassing Paradise Plains and Deep Creek (approximately 3500 ha). These study areas were originally selected to reflect a range of forest ages within the Mountain Ash estate more generally [20]. We again used a set of 100 000 randomly selected points, albeit confined to these smaller areas. We assigned each point to a moisture availability (TWI) class (as described above) after assessing its topographic characteristics, and to a land tenure class (also as described above). We used the same criteria as used previously [20] to assign old-growth (28 865 of the randomly selected points) and non-old-growth (714 135 of the randomly selected points) condition within the study areas.

3. Results

For all land tenures, the probability of dominance by Mountain Ash increased with TWI. Randomly selected points within the water catchment areas were more than twice as likely to be Mountain Ash ‘wet eucalypt’ than points within non-catchment forests (figure 2). Outside catchment areas, there were negligible differences in the probability of Mountain Ash between State Forest on the one hand, and protected tenures (National Parks and Reserves) on the other. Within water catchment areas, the probability of Mountain Ash (and related wet forest communities such as cool-temperate rainforest) being the dominant vegetation type increased more quickly with increasing TWI for protected tenures compared to State Forest tenures (figure 2).

The data on fire extent (figure 3) demonstrate a number of features. First, the extent of fire (% of points within each TWI class that burnt) decreased exponentially with water availability (see inset, figure 3) in both the 1939 and 2009 fire events across all tenures. TWI explained >85% of fire extent in Mountain Ash forests.

Land tenure variations in fire extent were equally clear. In 1939, Mountain Ash forests in State Forest tenures (column D) were almost three times as likely to burn as those in protected tenures (column A). In 2009, close to the same proportion (∼40%) of Mountain Ash burnt in both types of tenure. The frequency of Mountain Ash forest burnt in State Forest tenures (D) was one-third less in 2009 than it was in 1939, while that in protected tenures doubled (A). There were only small differences between 1939 and 2009 in extent of fire for State Forest tenure within catchment areas (column C), or for other protected tenures outside catchment areas (column B). Figure 3 also shows that drier sites (e.g. TWI <6) comprised the great bulk of the areas of Mountain Ash burnt (>80%) in both 1939 and 2009. Almost no stands of
Figure 3. Extent of fire (% of sample points that were burnt) in Mountain Ash within each topographic wetness index (TWI) for 1939 and 2009 fire years. Classes of TWI: <3, very dry; 3–6, dry; 6–9, medium; 9–12, wet; >12: very wet. Data based on 100,000 randomly selected points. Numbers above the columns indicate the total number of points for each land tenure type for each fire year. Insert shows the negative exponential relationship between fire extent and TWI (grouped by land tenure).

Mountain Ash in the wettest areas (TWI >12) burnt at all.

When we restricted our analysis to independently selected smaller areas (see section 2, again based on >100,000 random sampling points), results mirror those for the full fire areas with respect to land tenure (see SI figures 1 and 3 (available online at stacks.iop.org/ERL/16/044021/mmedia)). Tenure did not change fire extent. The results also show that mature stands of Mountain Ash were more likely found on southerly wetter aspects than stands of intermediate age (SI figure 2). In other words, forest ages were not evenly distributed with respect to aspect. Mature stands were more likely to be located on southerly wetter aspects than stands of intermediate age (see SI figure 2).

4. Discussion

Mountain Ash forests have long been known to be restricted by water availability. There are very few stands of Mountain Ash in areas with annual rainfall less than 1200 mm or on anything but deep soils with good structure and water holding capability. A result is that the distribution of Mountain Ash within the Central Highlands in Victoria is discontinuous [11]. Mountain Ash is replaced by other species of Eucalyptus, notably Eucalyptus obliqua (Messmate), as rainfall declines or as soil profiles become shallower and less able to hold water [11]. The data reported here make clear that the same feature—water availability—plays a major role in fire extent within the boundaries of high intensity bushfires (figure 1, see also [7]). Only the wettest topographies escape fire when extreme climatic conditions dry out the large loads of fine fuels (e.g. 20–30+ t ha\(^{-1}\), see [21]) that build up over time, as was the case in both 1939 and 2009.

Within the limits set by climate and soils, Mountain Ash forests encompass a wide range of slopes and aspects but are highly dissected. While most eucalypt forests and woodlands are water-limited [22], on steep southerly slopes, Mountain Ash forests become relatively energy-limited [23] and a midstorey of Nothofagus cunninghamii and Acacia spp. can develop. The non-water limited nature of large tracts of Mountain Ash forest is recognized via their consistent yield of water. That supply was tapped for the City of...
Protected land tenures were not an effective defense against wildfire in Mountain Ash stands (figure 3, SI figure 1). Land tenure is also confounded with other factors. For example, protected tenures (forested catchments, National Parks) contain the greatest proportion of the wettest and most productive stands of Mountain Ash. These are also the stands with the greatest fuel loads. Only under the driest seasonal conditions (and long droughts preceded both the 1939 and 2009 wildfires), are these fuels—especially the fine fuels—dry enough to burn. The type of tenure of Mountain Ash forests thus present a unique 'fire problem' once drought conditions prevail. Mountain Ash forests with State Forest tenure—representing a smaller proportion of the wettest locations and with somewhat less productive capacity—will be the first to reach critically low levels of fuel moisture. Mountain Ash forests in protected tenures will reach critical fuel moisture more slowly, but fuel loads will be even greater. The potential for wildfire and resulting fire intensity and severity will also be greater. The challenge for fire management could scarcely be more difficult.

While we examined the effects of land tenure— and State Forest tenure is open to logging—our study is not a test of the effects of logging on fire frequency in Mountain Ash forests per se. As shown clearly in figure 2, State Forest tenure within water catchments has a significantly reduced probability of being dominated by Mountain Ash compared to National Park tenure within water catchments. That probability also increases more slowly with TWI in State Forest tenure. When the consequences of the 1939 wildfire was compared to the 2009 wildfire, the extent of fire in Mountain Ash increased in protected tenures and decreased in State Forests. These changes over the 70 year period between fires could be due to a number of factors. As we note above, topography can easily confound efforts to isolate other effects, such as stand age, and their role in fire extent and severity. In more detail, and as might be expected, the extent of fire in Mountain Ash forests was far greater on dry sites (e.g. TWI = 3–6) than in any other area (figure 3). Dry sites with protected tenures in catchment areas showed a major increase in fire extent comparing the 1939 fires to the 2009 fires, while dry sites with State Forest tenure showed an equally large decrease (figure 3). Again, we emphasize that these results are not an explicit test of the effects of logging on frequency of burning within Mountain Ash forests. On the other hand, our data show that State Forest tenure (including all allowed activities) does not predispose Mountain Ash forests to wildfire.

We conclude that spatial patterns (and burn frequency) within high intensity wildfires in Mountain Ash forests are overwhelmingly driven by topographically determined availability of water (and its
The spatial patterns of fire reinforce the spatial distribution of Mountain Ash—and its tight control by water availability. Topographic controls on wildfires are increasingly recognized, especially for the severity of burning within small-medium sized fires [28] but also for fire occurrence within landscapes [23, 29]. The strength of control on the likelihood of stands of Mountain Ash being burnt within the two high intensity wildfires studied here is all the more remarkable for the diversity of the landscape and of the weather during both the 1939 and 2009 fires. Topographic wetness indices are a straightforward means of characterizing landscapes in terms of water availability and fire risks.

We also conclude that protected tenure is not an effective barrier to fire, nor can it mitigate the extent of fire. Managing risks to conservation values in Mountain Ash forests will need to remain focused on surrounding forests as there is no practical means of controlling fuel loads in the former. As used here, TWI can be used to identify areas at least risk even within fires of the greatest intensity and rate of spread. These are arguably natural ‘fire refugia’ (e.g. [30, 31]) for species that are otherwise threatened by repeated fires. As noted by others, it will be active land management that will be key to improving fire management [32–34]. Protected tenures are secure in Australia and many other western democracies (sensu Robinson et al [35]). However, wildfires do not discriminate by tenure and key issues such as persistence of Mountain Ash forests if inter-fire periods shorten [7], will need to be addressed on all tenures.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Author contributions

M A A conceived the study, M G extracted and analyzed the data and prepared the figures. M A A wrote the paper with input from all other authors. All authors contributed to discussions and to editing drafts of the manuscript.

Conflict of interest

The authors declare no competing interests.

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