# Nonlinear Effects of Stand Age on Fire Severity

Chris Taylor[1], Michael A. McCarthy[2], & David B. Lindenmayer[3]

[1] Melbourne Sustainable Society Institute, University of Melbourne, Parkville, Victoria 3051, Australia
[2] School of Botany, University of Melbourne, Parkville, Victoria 3051, Australia
[3] Fenner School of Environment and Society, The Australian National University, Canberra, ACT 0200, Australia

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**Correspondence**
David Lindenmayer, Fenner School of Environment and Society, The Australian National University, Canberra, ACT 0200, Australia.
Tel: 02 61250654; fax: 02 61250746.
E-mail: david.lindenmayer@anu.edu.au

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## Abstract

We quantify the relationship between forest stand age and fire severity using a detailed case study of Mountain Ash (*Eucalyptus regnans* Muell) forest burned in south-eastern Australia in 2009. We focused on two important areas of Mountain Ash forest that feature a range of growth stages and disturbance histories. Using probit regression analysis, we identified a strong relationship between the age of a Mountain Ash forest and the severity of damage that the forest sustained from the fires under extreme weather conditions. Stands of Mountain Ash trees between the ages of 7 to 36 years mostly sustained canopy consumption and scorching, which are impacts resulting from high-severity fire. High-severity fire leading to canopy consumption almost never occurred in young stands (<7 years) and also was infrequent in older (>40 years) stands of Mountain Ash. We discuss the significant forest conservation and management implications of these results for Mountain Ash forests as well as other similar biomes, where high-severity fire is a common form of disturbance.

## Introduction

Fire is a major ecological process in ecosystems worldwide (Bowman *et al.* 2009). It can influence the type of vegetation cover (Whelan 1995), levels and patterns of biodiversity (Lindenmayer *et al.* 2014a), nutrient cycling (Raison 1980), and carbon stocks (Keith *et al.* 2009). It also affects human communities through loss of life and property (Bowman *et al.* 2011). The sequence and characteristics of fires in an area is shaped by multiple biotic, abiotic, and anthropogenic factors that are not stable in space and time and create pervasive uncertainty (Dovers 2003). These uncertainties make predicting the spread and impacts of fires difficult (Leonard *et al.* 2014). The rates of fire spread, fire intensities, and other properties of fire vary widely (Collins *et al.* 2007; Gill 2012). The resulting impact of fire on vegetation, that is, the fire severity, is also variable (Keeley 2009).

Fire severity is defined as the extent of loss or consumption of the vegetation and other biomass as a result of fire. It describes how fire intensity affects ecosystems, where direct information on fire intensity can be absent and effects are often quite variable within and between different ecosystems (Keeley 2009). Many, often interrelated, natural factors influence fire severity. These include: (1) vegetation type (Bradstock *et al.* 2012); (2) the amount of fuel (Sullivan *et al.* 2012); (3) fire weather conditions (e.g., temperature, relative humidity, wind speed, and drought factor); and (4) timing (time of day, season and time elapsed since the preceding fire) (Collins *et al.* 2007; Price & Bradstock 2010).

Another key factor which can influence fire severity is past anthropogenic disturbance, such as logging (Thompson *et al.* 2007; Lindenmayer *et al.* 2011). This has been observed in tropical, temperate, and boreal forests, where anthropogenic disturbance and modification of native ecosystems has not acted in isolation, but has interacted with natural ecosystem disturbance (Thompson *et al.* 2007; reviewed by Lindenmayer *et al.* 2009). However, the risk that anthropogenic disturbance can influence fire severity is controversial (Ferguson & Cheney 2011; Attiwill *et al.* 2013). This makes it critical to examine interactions between fires and the environmental variables that influence them.

Here, we quantify relationships between prior anthropogenic disturbance and fire severity using a detailed case study of the Mountain Ash (*Eucalyptus regnans* Muell) forests in south-eastern Australia. Parts of these forests were burned by large wildfires in February 2009 (Cruz *et al.* 2012). Indeed, these fires were one of Australia's worst natural disasters, where 173 human lives were lost and over 3,000 properties destroyed (Gibbons *et al.* 2012). Several studies have analyzed the behavior and impact of this fire at a broad landscape scale (Cruz *et al.* 2012; Price & Bradstock 2012). Our study expands on these previous studies by focusing exclusively on fire severity impacts in Mountain Ash forests at the stand level. A paucity of stand-level analysis is a key knowledge gap, given the prevalence of logged and regenerated stands throughout not only Mountain Ash ecosystems, but also in other high productivity wet forest types elsewhere in Australia (Wood *et al.* 2014) and overseas (e.g., Franklin *et al.* 2002). We addressed this important knowledge gap by addressing the question: *How does stand age influence the severity of fire in Mountain Ash forest under extreme fire weather conditions?*

Major forest disturbances, including large high-severity wildfires, are likely to increase as a consequence of climate change (Bachelet *et al.* 2005; Cary *et al.* 2012). We therefore argue it is critical to better quantify the relationships between anthropogenic disturbances and fire severity and, in turn, consider their implications for how forest ecosystems are conserved and managed.

# Methods

## Study Area

Our case study focused on Mountain Ash forests affected by the February 2009 fires in the Central Highlands of Victoria, south-eastern Australia (Figure 1). These forests form visually spectacular stands containing trees that can exceed 100 m in height (Ashton 1976). They provide habitat for a number of threatened and endemic species, such as the Leadbeater's Possum (*Gymnobelideus leadbeateri* McCoy) (Lindenmayer *et al.* 2013) and the Baw Baw Frog *(Philoria frosti* Spencer) (Hollis 2004).

Forests dominated by Mountain Ash are located in water catchments critical for supplying water to the city of Melbourne and surrounding rural communities (Viggers *et al.* 2013). These forests support the largest known stores of terrestrial ecosystem carbon, with some sites containing over 1,800 t/C/ha (Keith *et al.* 2009). Mountain Ash forests have been a major source of pulpwood and sawlogs for industry since the 1930s (Lutze *et al.* 1999).

The main form of natural disturbance in Mountain Ash forests is wildfire, which typically occurs following dry summer conditions, particularly periods of prolonged drought (Mackey *et al.* 2002). Mountain Ash forests have experienced many fires including those in 1851, 1898, 1926, 1939, and 1983 (Griffiths 2001). The impacts of fire on these forests has been variable, and range from high-severity conflagrations resulting in stand replacement, to fires of lower severity that leave biological legacies (*sensu* Franklin *et al.* 2002) such as two or more age cohorts of trees (i.e., multiaged stands) (McCarthy & Lindenmayer 1998). Extensive salvage logging following the 1939 fires removed many of these biological legacies, creating extensive areas of even-aged stands after that conflagration (Mackey *et al.* 2002).

## Fires of February 2009

The months of January and February 2009 were characterized by intense fire activity across the state of Victoria, with 825 wildfires occurring and collectively burning 437,000 hectares (DSE 2009a). Fire activity peaked on 7 February, with extremely intense fire behavior and rapid rates of spread in the lead up to, and directly following, the passage of a cold front (Cruz *et al.* 2012). At this time, the Forest Fire Danger Index (FFDI), which correlates with fire behavior and depends on temperature, wind velocity, relative humidity and the Keeck–Byram Drought Index (Noble *et al.* 1980) (see Figure S1), reached unprecedented levels (Gellie *et al.* 2013). (See Methods section in Supporting Information for a description of how the FFDI was derived). It was during this time that the fire spread was at its most rapid and the fire was at its greatest intensity (Cruz *et al.* 2012; Gellie *et al.* 2013). Overall, 169 fires were burning across the state in the days following 7 February 2009 (DSE 2009a). Two of these, the Kilmore East and Murrindindi fires, burned large areas of Mountain Ash forest (Cruz *et al.* 2012; Price & Bradstock 2012).

The Kilmore East and Murrindindi fires were ignited around 11:45 and 14:55 hours, respectively. Leading up to the wind change driven by an approaching cold front, the Kilmore East and Murrindindi fires traveled approximately 55 and 33 km, respectively (Gellie *et al.* 2013). The cold front passed across the fires between 18:10 and 18:35 hours, resulting in the long north-eastern flank of the fire becoming the front (Cruz *et al.* 2012). In the hours following the south-westerly wind change, fire weather conditions moderated and the spread of the fire slowed. However, the fire continued to burn for another 26 days before it was contained. This was after efforts in control line construction and back burning to stop the spread of the fire (Gellie *et al.* 2013).

 

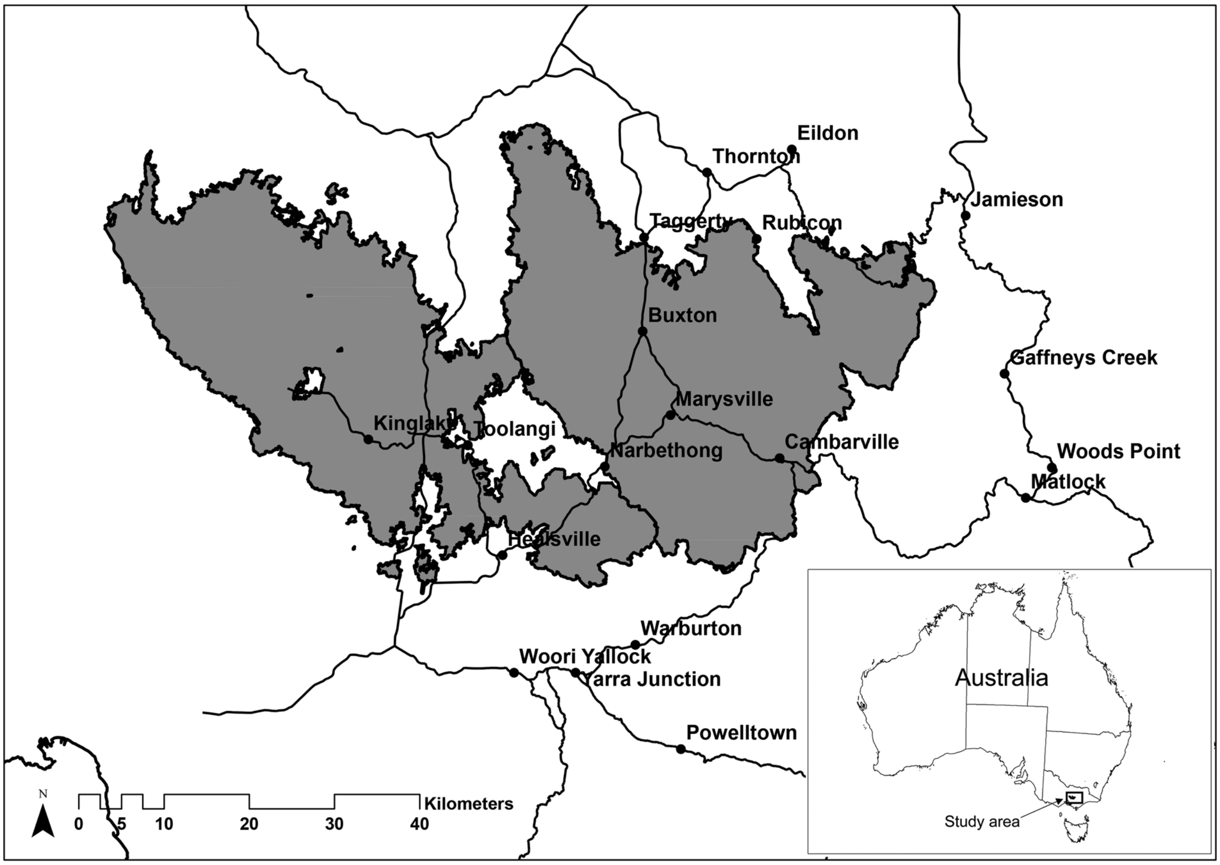


**Figure 1** Location of study area and extent of fire impacted area in the study region.

## Fire Progression

We mapped the progression of the 2009 fires, from the point of ignition to their full extent, using a series of isochrones (Gellie *et al.* 2013). These isochrones mark the spatial extent of the fires at 30–60 minute intervals to a spatial accuracy of 200–500 m and a temporal accuracy of 5 minutes. They were interpreted from fire severity patterns on postfire aerial photography or remote sensing and supplemented by videos, photographs and eyewitness accounts obtained from local people and staff from various Victorian Government organizations responsible for fire control. However, where such evidence was deficient, such as in remote areas, we used isochrones of lower confidence (Gellie *et al.* 2013) (Refer to Figure 2).

## Sample Stands

We determined the extent of Mountain Ash forest from maps of the "wet forest" ecological vegetation class (DSE 2005). We stratified this ecological vegetation class into six age classes at the time of the fire: 4–9 years, 10–14 years, 15–24 years, 25–40 years, 70 years, and 300 years (see Figures 3 and 4). Stand age determination was based on multiple datasets, with logging history data informing stand ages between 0 and 40 years (DSE 2011), State Forest Resource Inventory (SFRI) data (DSE 2007a) and data presented in Mackey *et al.* (2002) informing forest age of 70 years, and modeled old growth informing the forest age of 300 years (DSE 2007b). Although, the modeled old growth dataset does not describe stand age, the determination of 300 years was based on the findings presented by Lindenmayer *et al.* (2000a) (see Figures 5 and 6).

The type of disturbance resulting in the establishment of the stands prior to the fire, varied across the age classes. Stands in age classes between 0 and 40 years were mostly established following clearfell logging (DSE 2011). Stands in the 70 year age class were mostly established following the 1939 fires (Griffiths 2001). Extensive areas of this age class were subjected to postfire (salvage) logging for 20 years following the 1939 fires (Mackey *et al.* 2002). However, no historical records were kept on the timing, location, spatial extent and intensity of these past logging

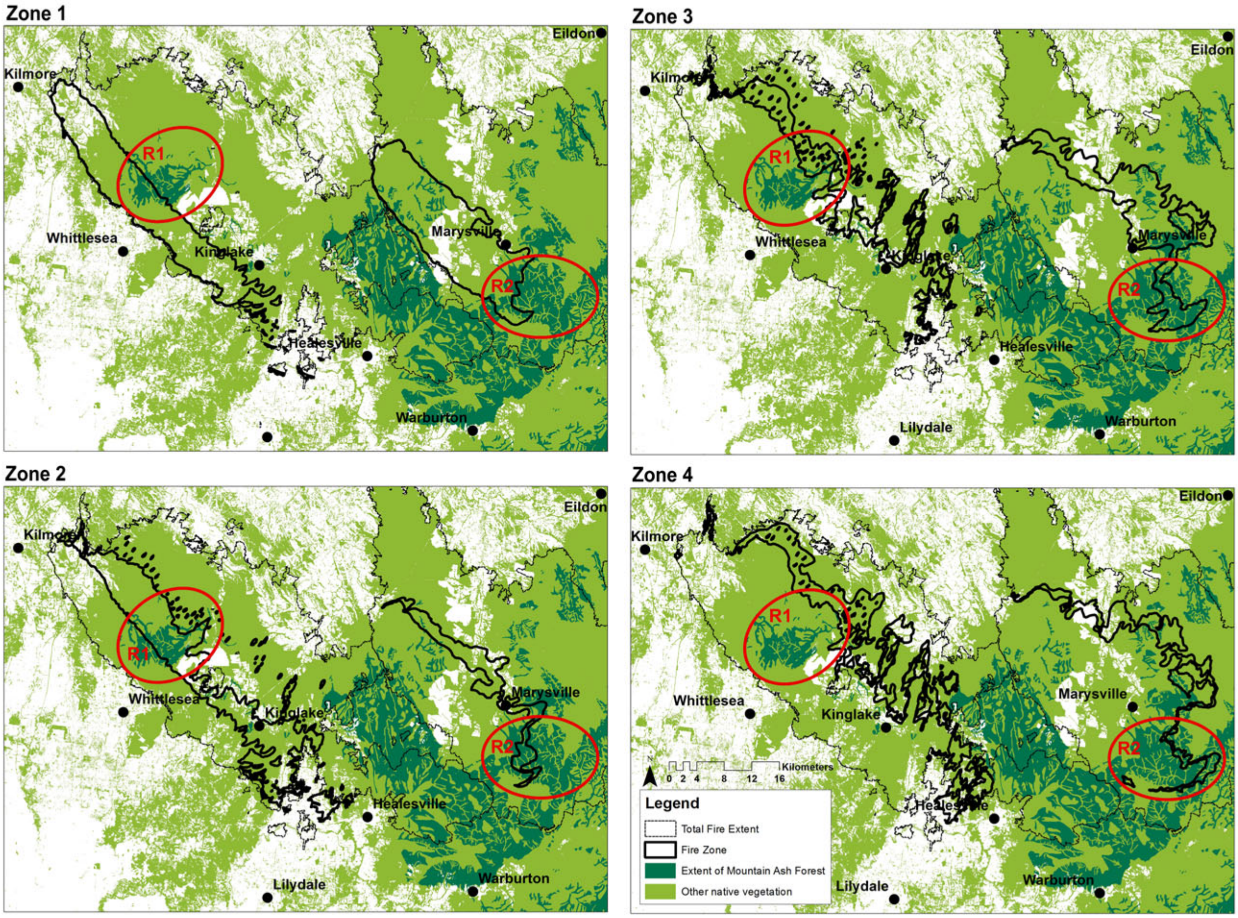


**Figure 2** Extent of fire affected forest before the wind change (Zone 1) and for the two hours following the wind change (Zones 2, 3, and 4). The extent of Mountain Ash forest is shown as dark green. Sample subregions show the areas of Mountain Ash Forest targeted for analysis. R1 shows the Mountain Ash stands at Mount Disappointment; R2 show Mountain Ash at Paradise Plains and Deep Creek.

operations, which made it difficult to determine whether stands were established after fire or following logging. The majority of stands in the 70 year age class were even-aged across the sites at the time of the fires. This indicates that postfire logging had occurred because most unlogged stands feature multiple cohorts of age classes (Lindenmayer *et al*. 2000a). Stands in the 300-year age class are located entirely within those closed water catchments where logging had been prohibited (Viggers *et al*. 2013).

We identified areas of Mountain Ash forest burnt by the 2009 fires under similar weather conditions. According to Price & Bradstock (2012), the magnitude and spread of the 2009 fires were strongly influenced by the severity of fire weather. We controlled for the effects of fire weather by constraining our analyses to areas burnt under similar fire weather conditions at similar times, thereby enabling us to quantify the effects of other variables that can influence fire severity such as slope, aspect, and stand age (Mackey *et al.* 2002).

We focused our study on areas burned under extreme fire weather conditions (determined as places where the FFDI exceeded an index value of 75 using the CFA Fire Danger Rating System) and for the period immediately following thereafter. The two reasons for selecting this period of the fire were first, to examine the impact of the fire on Mountain Ash forest under extreme weather conditions, when tree death is most likely, and second, to maintain consistency in weather conditions and the type of fire in our analyses. Human attempts to control the fire were conducted when fire weather conditions moderated for several hours following the wind change. This significantly alters the behavior of the fire, because backburning is widely applied throughout native vegetation with the aim of protecting assets, such as property and infrastructure.

 

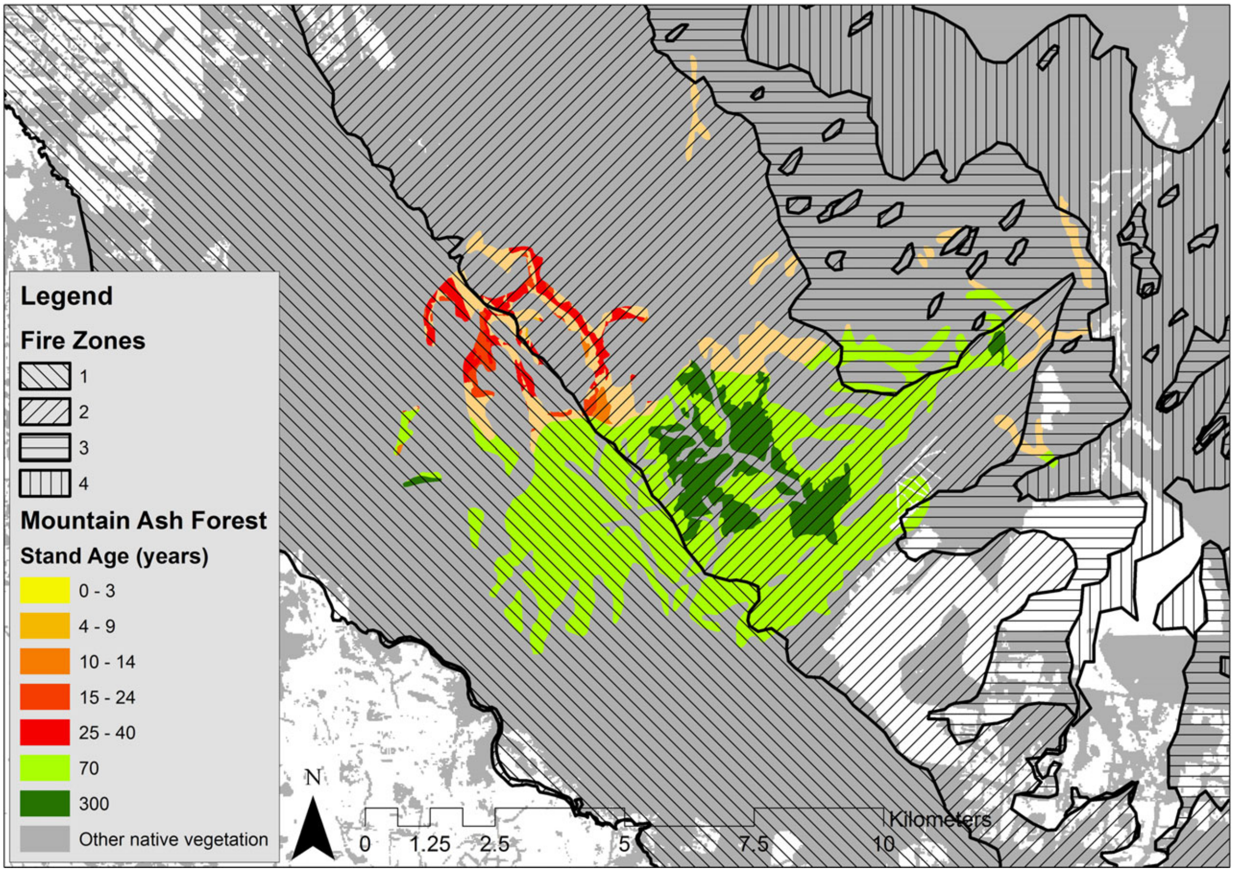


**Figure 3** Fire zones and stand age of Mountain Ash forest across R1 (Mount Disappointment).

We mapped the spatial extent of the area burned when the FFDI was extreme and for the period immediately following thereafter using the fire isochrones (Gellie *et al.* 2013). To facilitate our analysis, we identified two subregions dominated by Mountain Ash forest. One was located on the plateau surrounding Mount Disappointment (R1) and the other on the plateau encompassing Paradise Plains and Deep Creek (R2) (Figure 2). Subregions R1 and R2 are 5,984 and 3,569 hectares, respectively, and approximately 56 km apart (see Figure 2; and Figures S2 and S3).

Within each subregion, we defined four time periods relative to the time of the wind change, which we refer to as zones (Figure 2; Figures S2 and S3). For the Kilmore East fire, which covered the R1 subregion, the zones were: (1) areas burnt between ignition and the wind change at 17:50 hours; (2) areas burnt between the wind change and 18:35 hours; (3) areas burnt between 18:35 and 19:15 hours; and (4) areas burnt between 19:15 and 20:25 hours. For the Murrindindi fire, which covered the R2 subregion, the four zones were: (1) areas between time of ignition and the wind change at 18:45 hours; (2) areas burnt between the wind change and 19:30 hours; (3) areas burnt between 19:30 and 20:30 hours; and (4) areas between 20:30 and 21:30 hours. Zone (1) was burnt under the highest FFDI. Zones (2), (3), and (4) were burnt under declining FFDIs in relation to time following the wind change (refer to Figure S1).

## Fire Severity Data

We obtained fire severity maps for Mountain Ash forest in our two study regions from the Victorian Government (DSE 2009c). These maps were based on a fire severity index developed through digital processing of the prefire and postfire imagery acquired by the SPOT 4 and 5 Satellite. These data comprised the Short Wave Infrared (SWIR) and Near Infrared (NIR) bands that were analyzed through a Transform Vegetation Index (TVI). Fire severity was scaled as an index gauging the magnitude of canopy scorch resulting from fire (DSE 2009b). This index was then compared against ground-based information

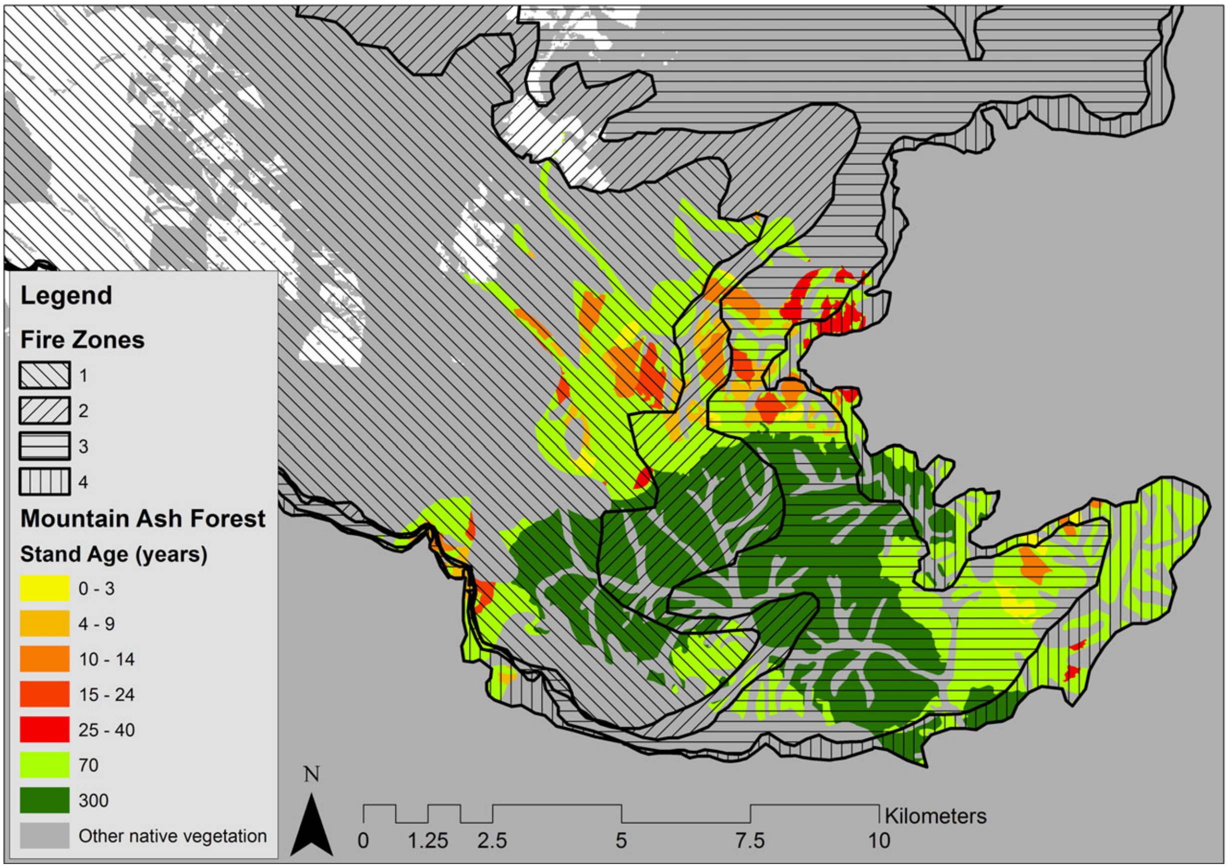


**Figure 4** Fire zones and stand age of Mountain Ash forest across R2 (Paradise Plains and Deep Creek).

and split into five classes (DSE 2009c). This process determined the statistical association between fire severity observed on the ground and that derived from satellite data. These five classes ranged from a canopy consuming fire (the most severe) to no canopy scorch (the lowest) (see Table S1).

We assumed that the top two severity classes caused widespread tree mortality in Mountain Ash forest. The highest severity class was canopy consumption in which 70–100% of the canopy was burnt. The second most severe class was canopy scorch, where 60–100% of eucalypt and noneucalypt canopies were scorched, but the leaves remained on the branches immediately following the fire. We refer to these two classes as "high-severity" fire. The assumption that these two fire severity classes resulted in tree mortality was based on studies by Smith & Woodgate (1985) and Vivian *et al.* (2008). In a study of fire damage following the 1983 "Ash Wednesday" fires in Mountain Ash forest that was conducted in an area located approximately 25 km south of subregion 2 in our study, Smith & Woodgate (1985) found that fire severity classes of complete canopy consumption, canopy scorch and 75–99% canopy scorch resulted in widespread tree mortality. Trees subject to lower severity fire were considered capable of surviving. In Alpine Ash (*Eucalyptus delegatensis* Barker) trees (which is a similarly fire-sensitive species to Mountain Ash), Vivian *et al.* (2008) found that fire severity classes of canopy consumption and severe canopy scorch resulted in 98.9% tree mortality and lower severity classes resulted in only 17.5% tree mortality, with much of the prefire stand surviving.

## Data Sampling

We sampled fire severity data using a square grid at 100 m intervals. The points of the grid formed our sites. Our response variables were the fire severity classes that resulted in the mortality of Mountain Ash trees. These classes were represented as either present (1) or absent (0) for each site in our analysis. We calculated these variables using Geostatistical Analyst software (ArcGIS 10) (ESRI 2011) for fire severity patterns in the four zones.

 

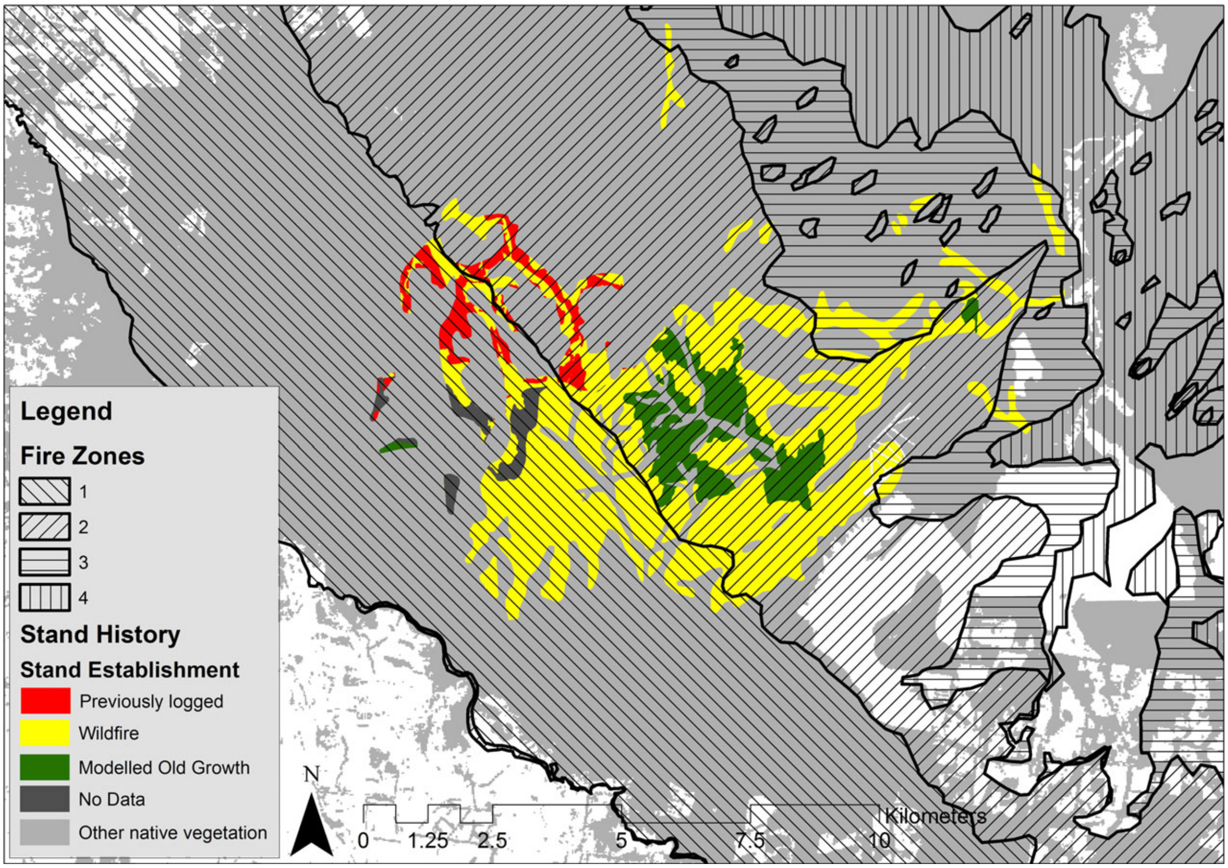


**Figure 5** Fire zones and disturbance history in Mountain Ash forest across R1 (Mount Disappointment).

Our procedure generated data for 9,934 sites. We pooled the presence and absence of canopy consumption and the combined canopy consumption and scorch within each zone and across the zones. We displayed the results for each zone separately, which allowed us to compare the different subregions and time zones. We also displayed the overall average of the presence and absence of canopy consumption and the combined canopy consumption and scorch across all the zones, to draw comparisons of fire severity between the zones. In the Kilmore East fire, 1,256 sites of Mountain Ash forest burnt prior to the wind change at 17:50 hours (Kilmore East Zone 1), 2,061 sites burnt from the wind change up to 18:35 hours (Zone 2), 207 sites burnt between 18:35 and 19:15 hours (Zone 3), and 300 sites burnt between 19:15 and 20:25 hours (Zone 4). For the Murrindindi fire, 1,582 sites of Mountain Ash forest burnt prior to the wind change at 18:45 hours (Murrindindi Zone 1), 1,069 sites burnt from the wind change up to 19:30 hours (Zone 2), 2,249 sites burnt between 19:30 and 20:30 hours (Zone 3), and 961 sites burnt between 20:30 and 21:30 hours (Zone 4). The total number of sites was more than could be analyzed using our multivariate probit modeling approach. We therefore took a random sample of points, stratified on stand age and zone defining time of fire impact, for subsequent statistical analysis. Stratifying the selection by age and zone ensured good coverage of the area and previous disturbance history of Mountain Ash forest affected by the fires. Where the requisite number of sites for an age class was not available in a subset, we selected all sites in that age class. In total, we analyzed data from 633 sites (see Table S2). We assumed that sites in Kilmore East and Murrindindi were independent of each other given the distance between them (~56 km). This was supported by the estimated correlations, which were very close to zero at distances >1 km.

## Statistical analyses

We analyzed our data with a multivariate probit regression model that accounted for correlation in the occurrence of fires among sites (Chib & Greenberg 1998). Accounting for correlation is important because not doing so

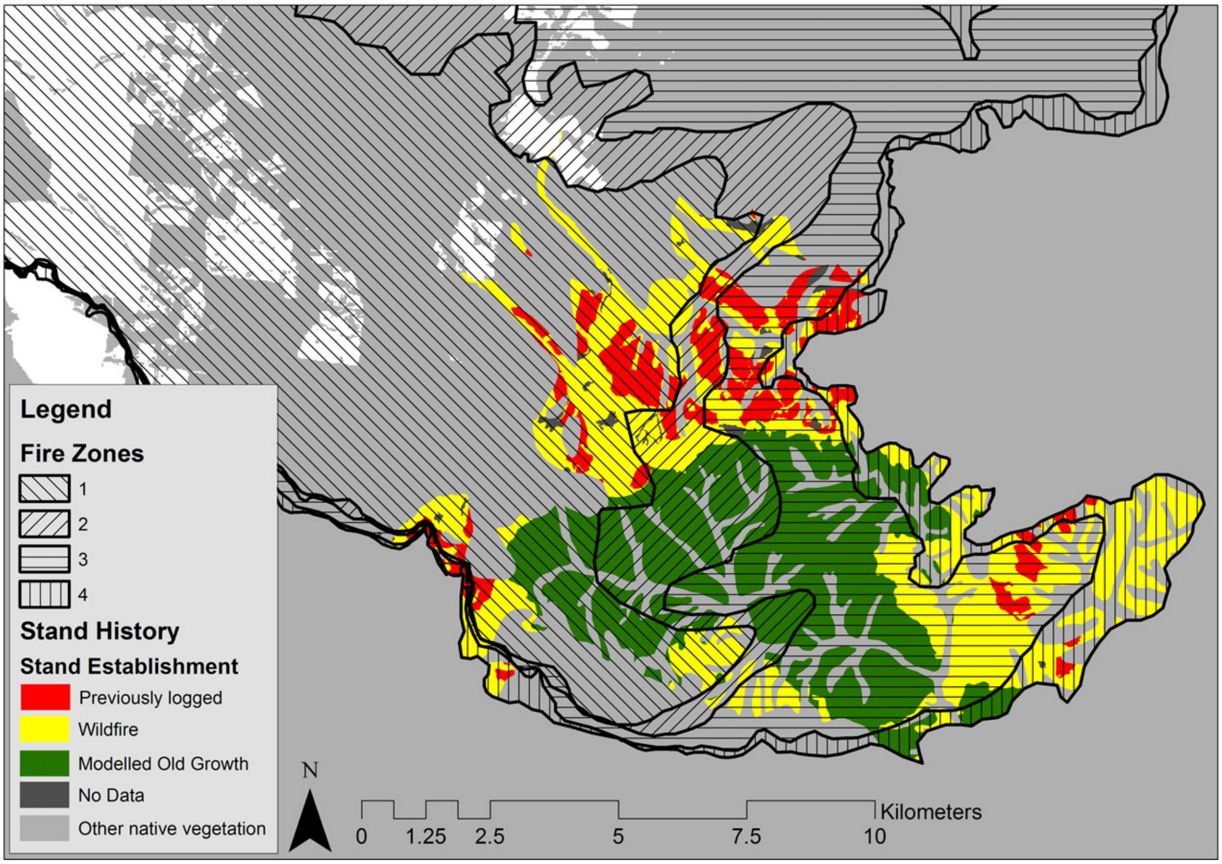


**Figure 6** Fire zones and disturbance history in Mountain Ash forest across R2 (Paradise Plains and Deep Creek).

would lead to unmodeled pseudo-replication, with consequent overestimation of model precision and possible bias of parameter estimates.

Probit regression is a form of generalized linear modeling that uses the cumulative distribution function of the standard normal distribution to convert a linear predictor to a probability (McCullagh & Nelder 1989). We modeled the occurrence of a particular fire severity class as a function of three explanatory variables: stand age; aspect; and slope. Because fires burn more intensively when traveling uphill, we measured aspect as the cosine of the angle between the direction of the prevailing wind and the aspect. We calculated slope in degrees. Due to the possible interaction between slope and aspect on fire behavior, we included an interaction term for these two measures. McCarthy *et al.* (2001) suggested that, in Mountain Ash forests, the probability of fire might first increase with time since fire and then decline. More specifically, McCarthy *et al.* (1999) also suggested a particular functional form for this relationship, although it was based on expert judgment rather than empirical data. To allow the model to fit a functional form similar to that suggested by McCarthy *et al.* (1999), we used an additive function of the reciprocal of stand age $1/t$ and the square of this term $1/t^2$. Thus, the linear predictor was for site $i$:

$$m_i = \beta_0 + \beta_1/t_i + \beta_2/t_i^2 + \beta_3\varphi_i + \beta_4\cos(\theta_i - \psi_i) + \beta_5\varphi_i\cos(\theta_i - \psi_i), \quad (1)$$

where $t_i$ is the age of the stand at the time of the fire, $\varphi_i$ and $\theta_i$ are the slope aspect of the site, $\psi_i$ is the direction from which the wind was blowing and $\beta_0$–$\beta_5$ are regression coefficients that were estimated. The effects of topography ($\beta_3$, $\beta_4$, and $\beta_5$) appeared to be weak. For example, parameter estimates for $\beta_3$ and $\beta_4$ were almost exactly zero, while the parameter estimate for $\beta_5$ suggested a small and uncertain increase in risks for sites facing toward the prevailing wind (estimate and 95% CI of 0.18 [−0.007, 0.043]) for the canopy consumption model. These models with topographic effects also estimated almost identical effects of stand age as models without these effects, so we report the results of a simplified statistical model that excluded these terms:

$$m_i = \beta_0 + \beta_1/t_i + \beta_2/t_i^2 \quad (2)$$

 

We used a model in which correlation in the occurrence of high-severity fire was a declining function of the distance between sites. The correlation in the latent normal distribution between two sites $i$ and $j$ was:

$$\rho_{ij} = \exp(-\varphi d_{ij}) \quad (3)$$

where $d_{ij}$ is the distance between sites $i$ and $j$, and $\varphi$ controls the rate at which the correlation declines with distance. Thus, the correlation approaches 1 as the distance between sites approaches 0 and it approaches 0 as the distance increases. This is equivalent to the model that McCarthy & Lindenmayer (1998) used to *simulate* fire in mountain ash forest. Here, we use the same basic model to *estimate* the probability of fire occurrence and the nature of the correlation.

We fitted the models using Bayesian MCMC methods in OpenBUGS (Spiegelhalter *et al.* 2012). Vague priors were used to ensure the results were driven by the data. For the regression coefficients ($\beta_j$), normal distributions with mean of 0 and standard deviation of 1,000 were used. For the rate at which the correlation decline with distance ($\varphi$), we used a uniform prior on the interval [0, 20]. We took 50,000 MCMC samples after discarding the first 100,000 as a burn-in. This burn-in was more than sufficient to ensure the samples were drawn from the stationary distribution, which was assessed by inspection of history plots in OpenBUGS as well as from running two Markov chains with different initial conditions.

## Results

Our analyses revealed the occurrence of canopy consumption was strongly correlated with the age of the stands ($\beta_1$ and $\beta_2$) (Figure 7). In contrast, the effects of topography ($\beta_3$, $\beta_4$, and $\beta_5$) appeared to be weak. Canopy consumption rarely, if ever, occurred in stands younger than 7 years. However, the probability of canopy consumption increased rapidly with age up to approximately 15 years ($m_i \sim 0.8$). In stands older than 15 years, the probability of canopy consumption decreased with age, such that it rarely occurred in stands aged around 300 years ($m_i \sim 0.1$). Previous disturbance history prior to the fires was variable, with stands between 0 and 40 years being established following clearfell logging, stands of 70 years being established following the 1939 fires, and extensive postfire logging and stands of 300 years previously established following past fires.

The relationship between probability of canopy consumption and stand age was similar across the four zones defining time of fire impact, suggesting that the reduced probability of canopy consumption in young stands less than 7 years and those aged around 300 years was not simply an artifact of subsampling from our dataset.

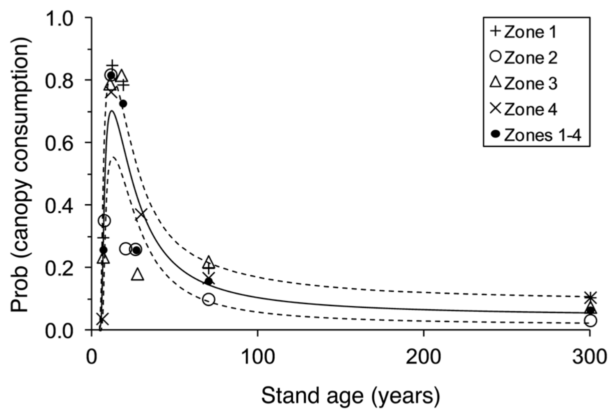


**Figure 7** Probability of canopy consumption versus stand age based on data from the Kilmore East and Murrindindi Fires during the periods before and after the wind change on 7 February 2009. These time periods are indicated by the different zones. The points are average ages and proportion of forest experiencing canopy consumption for each of six age classes, and for each of the four zones (Figure 2), and for all four zones combined. Only data with 15 or more data points are shown to reduce noise arising from small sample sizes. The solid line is the mean of the posterior prediction of the probit regression model fitted to a stratified sample of the data, and the dashed lines are 95% credible intervals.

Rather, it was spatially consistent under extreme weather conditions and the time periods immediately following the wind change.

We found that canopy consumption or canopy scorch rarely occurred in stands of Mountain Ash younger than 7 years. Similarly to canopy consumption alone, the proportion of forest sustaining canopy consumption or canopy scorch increased to a maximum at around 15 years of age, where most of the stand sustained a high-severity fire ($m_i > 0.9$). The probability declined after 15 years, but less quickly with increasing age than for the probability of canopy consumption alone (Figure 8). At 300 years, the probability of stands sustaining fires of canopy consumption or canopy scorch declined to around 0.7 ($m_i \sim 0.7$). This pattern was again consistent for all four time periods. However, the range of probability across the age class of 300 years shows a significant shift relative the range in younger age classes back to 15 years (Figure 8).

The probit regression models supported the analysis of the raw data, although the probit regression may have underestimated the degree to which the probability of severe fire changes with forest age (Figures 7 and 8). The regression coefficient $\beta_1$ is clearly greater than zero and $\beta_2$ is clearly less than zero (i.e., the 95% CIs do not encompass zero), meaning that the data strongly indicate that the probability of fire was maximized at intermediate ages (Table 1). These maxima were achieved at

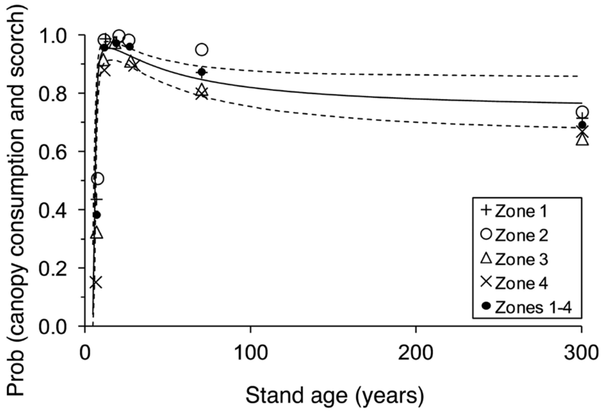


**Figure 8** Probability of canopy consumption or canopy scorch versus stand age based on data from the Kilmore East and Murrindindi Fires during the periods before and after the wind change on 7 February 2009. These time periods are indicated by the different zones. The points are average ages and proportion of forest experiencing canopy consumption for each of six age classes, and for each of the four zones (Figure 2), and for all four zones combined. Only data with 15 or more data points are shown to reduce noise arising from small sample sizes. The solid line is the mean of the posterior prediction of the probit regression model fitted to a stratified sample of the data, and the dashed lines are 95% credible intervals.

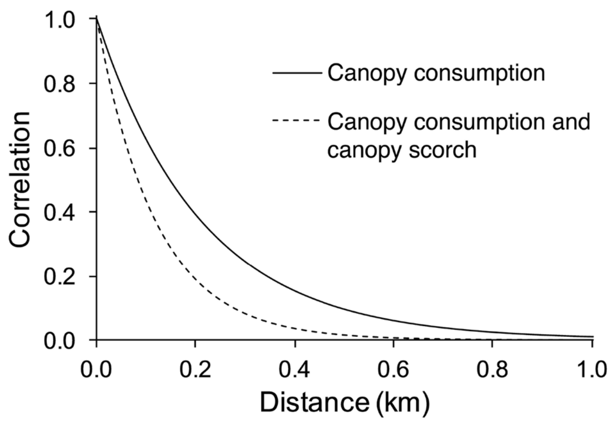


**Figure 9** Estimated correlation in the occurrence of canopy consumption (solid line) and canopy consumption or scorch (dashed line) for pairs of points as a function of distance between them, based on the probit regression model (Chib & Greenberg 1998) and assuming a correlation function given by Equation (3).

approximately 15 years for both classifications of severe fires (Figures 7 and 8). The occurrence of high-severity fire was, as expected, clearly spatially correlated, with strong positive correlation at short distances that declined to near zero at distances greater than 0.5–1 km (Figure 9).

## Discussion

The potential relationships between anthropogenic disturbance and fire severity of natural forests have been controversial. The review by Lindenmayer *et al.* (2009) précised evidence from a range of forest types around the world and suggested that while strategic forms of logging in dry forests can reduce fire severity, the reverse is true in moist forests, including boreal forests (Krawchuk & Cumming 2009), coniferous forest of north-western North America (Thompson *et al.* 2007) and tropical forest worldwide (Cochrane & Barber 2009). In the analyses that we report here, we identified a strong relationship between the age of Mountain Ash stands and the occurrence of canopy consumption and canopy scorch under extreme weather conditions in the February 2009 fires. We further discuss our findings in the remainder of this article. We conclude with a discussion of the implications of our work for forest management and forest biodiversity conservation.

### Why might stand age influence fire severity in Mountain Ash forests?

Our analyses revealed that stand age was a dominant variable influencing fire severity in stands of Mountain Ash forest for our study areas. The lowest fire severity impacts were sustained in stands less than 7 years old. We observed the inverse of this trend in age classes between 7 and 36 years, where the greatest proportion of stands sustained either canopy consumption or canopy scorch, with the maximum around the age of 15 years. These younger aged stands were established following clearfell logging.

**Table 1** Parameter estimates of the multivariate probit regression for canopy consumption and for fires that burn or scorch the canopy. The values are the mean of the posterior estimates and 95% credible intervals

| Parameter | Canopy consumption | Canopy consumption or Scorch |
|---|---|---|
| $\beta_0$ (intercept) | −1.82 [−2.21, −1.38] | 0.63 [0.34, 1.05] |
| $\beta_1$ ($1/t$) | 58.2 [41.8, 73.7] | 31.2 [12.6, 44.5] |
| $\beta_2$ ($1/t^2$) | −358.3 [−470.9, −255.6] | −223.8 [−314.2, −107.4] |
| $\varphi$ (decay of correlation with distance) | 4.7 [2.4,8.3] | 8.34 [1.81, 18.8] |

 

Interestingly, maximum fire severity around this age has been observed in other forest types, such as conifer plantations in the Klamath Mountains in southwest Oregon and northwest California in the United States (Thompson *et al.* 2011). Older Mountain Ash stands of 70 years and 300 years displayed low incidences of canopy consumption and the 300 year age class showed relatively lower levels of scorch, but much less than canopy consumption alone. These stands were previously established following major fire events in 1939 (70 years) (and possibly post fire logging) and after fires in the 1700s (300 years).

Several key factors may lead to different fire severity impacts among stands of different age with stands aged 7–36 years being particularly susceptible to canopy consumption or canopy scorching high-severity fire. First, for young stands established following clearfell logging, the logging practice itself alters the architecture of the forest. Large old trees are removed or lost from these sites. Initially, the slash burn following logging removes a large proportion of the available fine fuel that would sustain a fire. The newly established trees are characterized by high stem densities within the first 7 years of growth, with over 200,000 stems per hectare being recorded (Ashton 1976). However, the rate of self-thinning in regenerating stands of Mountain Ash trees increases rapidly from this early stage of growth until 40–80 years old, where 126–227 stems per hectare have been recorded, respectively (Ashton 1976). Similarly to young Australian Alpine Ash forests (which are ecologically similar to the stands targeted in our investigation), the vegetation of young Mountain Ash is well-aerated and comprises a horizontally and vertically continuous fuel layer that is highly flammable (Bowman *et al.* 2014). Natural self-thinning creates large amounts of fine fuels from suppressed plants in the early stages of regrowth, which, upon dying and drying out, become more susceptible to fires. In this context, Florence (1994, p. 24) explained that: "*Where regrowth develops following a severe perturbation, the forest floor biomass builds up rapidly to a point of peak fuel energy during the forest's rapid early growth stage. This point may be as soon as 35 years in stands of fast growing species*." This rapid accumulation of fine fuels during the early stages of growth in Mountain Ash forest, and its greater susceptibility to either canopy-consuming or canopy-scorching fire, places younger stands at greater risk of being eliminated from a site if a high-severity fire occurs. This is because the trees would be killed prior to producing seed (i.e., <20 years of age) (Mackey *et al.* 2002). This assumption is similar to the finding of Bowman *et al.* (2014), who observed a 97% attrition rate among juvenile trees in stands of Australian Alpine Ash forests that were recovering from a previous recent fire. However, the reasons why the crowns of very young stands (<7 years) are less likely to be damaged remain unclear, but they may be associated with the absence of large amounts of dead fine fuels at this growth stage, possibly because the process of rapid self-thinning has not yet commenced. The mortality of regeneration in these stands is presently unknown and is a topic of further research.

A second reason that stands aged 7–36 years old are at risk of canopy consumption or canopy scorch may be related to their limited height. A fire consuming ground-based fuel in such stands has the potential to burn the tree canopy at a lower severity than the canopy of an older forest (Mackey *et al.* 2002; Price & Bradstock 2012). In a similar study of conifer plantations in the United States, Thompson *et al.* (2011) explained that a high canopy-base-height is a likely explanation for decreasing canopy damage in older stands. A low canopy height is also compounded by increased bulk density, which is more abundant in fine fuels.

Third, young stands regenerating after clearfell logging have an altered floristic composition which may influence fire severity. Species characteristic of wet forests, such as the soft tree fern (*Dicksonia antarctica*), are significantly less abundant on logged sites (Ough 2001). These species cast dense shade, which influences rates of drying on the forest floor and hence moisture content of fine fuels (Wood *et al.* 2014).

Other factors may have an important effect on relationships between stand age and fire severity. For example, older aged stands of Mountain Ash forest accumulate large quantities of coarse woody debris and these are typically colonized by dense and luxuriant moss mats (Lindenmayer *et al.* 1999) that have very high water holding capacity. In addition, older aged stands of Mountain Ash forest are more likely to develop a luxuriant understorey layer that can be dominated by Gondwanic rainforest elements, such as Myrtle Beech (*Nothofagus cunninghamii*) (Lindenmayer *et al.* 2000a,b). These understorey layers limit light penetration to the forest floor, helping development of cool and moist microclimatic conditions that are unfavorable to fire propagation. Reduced flammability of rainforest was recognized by Wood *et al.* (2014).

## Limitations of analysis

The key result of this empirical study was a nonlinear relationship between stand age and fire severity, in which trees in young forest are more likely to be impacted and killed by fire than those in older forests or very young forest (<7 years). The evidence for this relationship was compelling and it was broadly consistent with that from other studies, both in Australian wet eucalypt forests (e.g., Price & Bradstock 2012) and moist forests elsewhere in the world (e.g., Thompson *et al.* 2007). Nevertheless, we recognize there were some limitations to our study, although these were unlikely to have major impacts on our general findings. First, fire severity information in our study was based on remotely sensed data calibrated against field observations and assigned to five fire severity classes. This dataset and others similar to it used in other studies (e.g., Collins *et al.* 2007; Thompson *et al.* 2007; Bradstock *et al.* 2010) provide a useful general indication of the immediate postfire impact on vegetation, but do not distinguish between age classes nor does it include measures of the long-term survival of fire-impacted stands.

A second limitation was that there has been poor historical recording keeping of data on the relatively large areas of forest subject to postfire logging, particularly after the 1939 fires. Salvage logging removes biological legacies remaining after a fire and which might otherwise have persisted in the regenerating stand (Lindenmayer *et al.* 2008). This removes the possibility of monitoring long-term impacts resulting from fire across specific age classes that have been targeted for such treatment.

## Comparisons with other studies on the February 2009 fires

The results of this investigation build upon those of previous studies conducted on the 2009 fire (e.g., Price & Bradstock 2012), as well as those on other fires in Australia (e.g., Collins *et al.* 2007; Murphy & Russell-Smith 2010; Bowman *et al.* 2014). The study by Price & Bradstock (2012) used the same fire severity dataset as in our study, but they applied it across broader landscapes, multiple fire events, and longer time frames (extending several days following ignition of the fire). In addition to determining that weather was the primary influence on fire severity, they found that the probability of canopy consuming fires in Ash forest was higher in recently logged areas than in areas less recently logged and in more recently burnt areas than those less recently burnt. Price & Bradstock (2012) used a logistic (binomial) regression to develop predictive models of the probability of occurrence of crown fire and understorey fire. They used a sample of grid points with 500-m separation across the multiple fire impacted areas to match the ridge valley distance across the fire impacted areas. They included dry, damp and wet forest in their analysis. Our study examined stand level responses to the 2009 fire. At this scale, we were able to detect a nonlinear response, with stands younger than 7 years and older than 40 years experiencing very little canopy consumption, but the highest impact being experienced at approximately 15 years old.

The study by Attiwill *et al.* (2013), which also analyzed the fire severity impacts of the February 2009 fires, differs from our study and those of Price & Bradstock (2012). Attiwill *et al.* (2013) argue that there is no relationship between fire severity and stand age across wet *Eucalyptus* forest (including Mountain Ash). Differences between the results of our investigation and those by Attiwill *et al.* (2013) likely occurred for several key reasons. First, Attiwill *et al.* (2013) did not differentiate between areas burnt under extreme fire weather conditions from those burnt under low to moderate weather conditions. Second, they did not differentiate areas that were burnt by the fire itself from those areas treated with human induced back-burning. Third, they downplayed the significance of the extensive areas of young stands (>7 years) that had been established following clearfell logging and which burned at a high severity in the 2009 wildfires. Finally, Attiwill *et al.* (2013) did not quantitatively analyze patterns of fire severity across the landscape through formal analysis (see Bradstock & Price 2014).

## Implications for forest management and forest biodiversity conservation

The results of this investigation have some important and often intimately interrelated implications for management and conservation, particularly in those moist forest environments that are subject to intensive and extensive logging operations and where high-severity fires can occur.

The elevated risks of high-severity fire in young stands regenerating after logging, uncovered in this study and in previous work (e.g., Thompson *et al.* 2007; Price & Bradstock 2012), suggests there is a need for forest managers to carefully consider the amount and spatial distribution of forest age classes in wood production landscapes. For example, there may be a need to schedule harvesting operations to limit the total amount of young forest in a given landscape. Forest planning may be required to avoid wood production landscapes from becoming heavily dominated by extensive and contiguous areas of, for example, 10–40 years forest that is prone to canopy-consuming fire.

There may be other, broader implications of stand age-fire severity relationships in moist forests such as those associated with the overall rotation time across wood production landscapes. For example, in the Mountain Ash forests of Victoria, many stands have been cut on a rotation as frequent as 48 years to maintain wood flows (Squire *et al.* 1991). Given the maintenance of these stands as young forests, which if burned, are at risk of high-severity fire, there may be a need to reassess

 

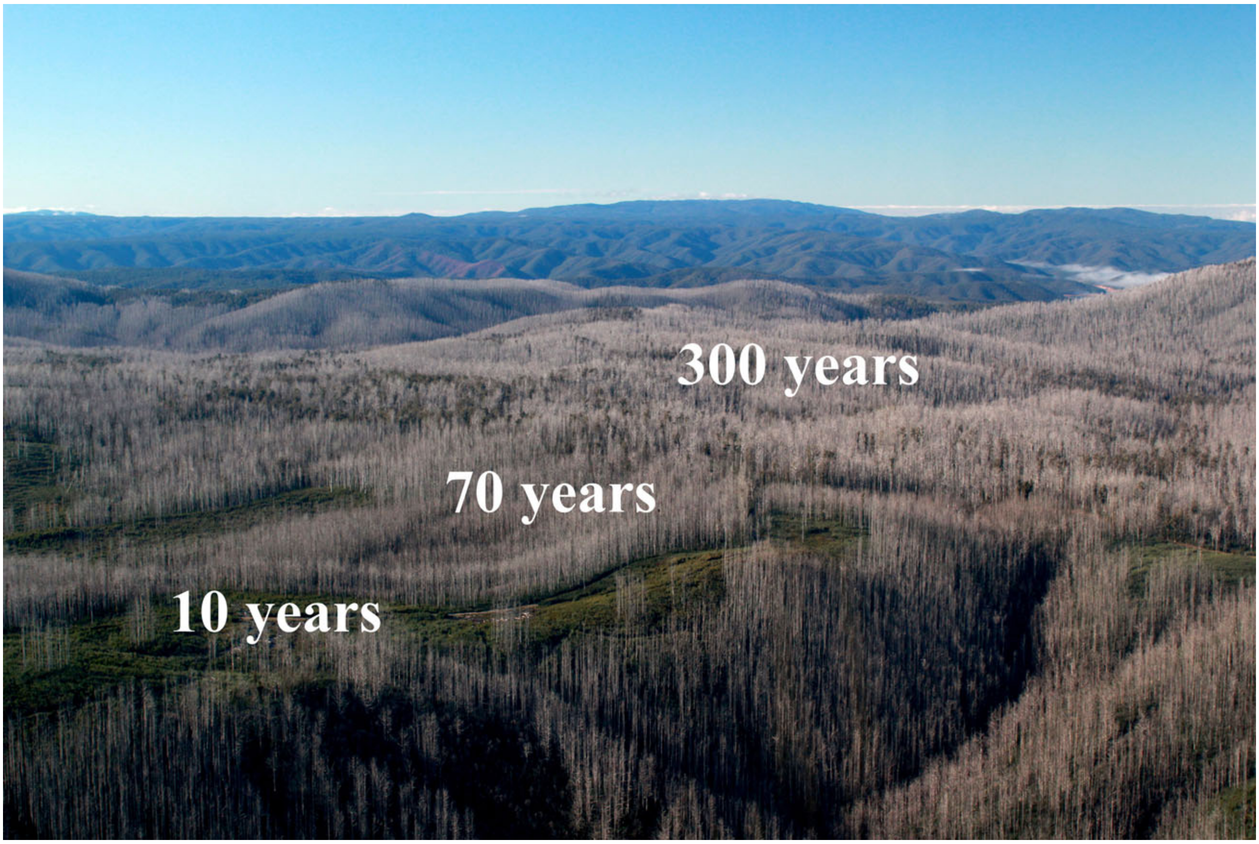


**Figure 10** Aerial image of subregion (R2), showing stands of fire impacted Mountain Ash forest across Deep Creek and Paradise Plains in 2013, 4 years following the February 2009 fires. The areas where live trees are present fall within the modeled old growth sites. These forests were aged around 300 years at the time of the 2009 fire. The forests in the foreground consist of a mixture of very young stands (<7 years), young stands (8–40 years) and stands originating from the 1939 fires (70 years). These areas (8–40 and 70 years) are largely absent of live trees. (Note: image was taken in April 2013—4 years after the fire).

rotation times to increase the interval between repeated logging events in the same stand.

A further key implication of our findings relates to the impacts of young flammable stands on the ecological integrity of adjacent older forests, which can be critical for the persistence of disturbance-sensitive taxa in otherwise logged landscapes (Gustafsson *et al.* 2012). Several studies in a range of moist forest ecosystems have indicated there can be strong spatial autocorrelation in patterns on fire spread (Whelan 1995; McCarthy & Lindenmayer 1998). This makes it important to determine the influence of elevated fire severity in logged and regenerated stands on adjacent undisturbed areas. In this context, a key research task will be to determine both the risks posed by young logged forests for neighboring older stands and what size of old growth patches might be needed to reduce spatial contagion in high-severity fire across otherwise logged landscapes.

The results of our work underscore the importance of stands of old forest in ecosystems that are subject to high-severity fire. Indeed, although we observed widespread mortality of Mountain Ash trees across all age classes over 7 years of age, there was a greater probability of tree survival in older (300 years) stands than in the younger age classes (Figure 10). Surviving large old trees are critical postdisturbance biological legacies that play many key ecological roles like storing large amounts of carbon and providing habitat for biodiversity (Lindenmayer *et al.* 2014b). They also can be critical for promoting the regeneration of stands after disturbance (Bowman *et al.* 2014).

The conservation and management implications of our findings highlight the critical importance of quantifying relationships between fire and anthropogenic disturbance and, in turn, taking steps to ensure that risks of elevated increased fire severity are mitigated wherever possible. We argue that human disturbances, like clearfell logging, can add further to the risk and should be minimized where possible. Such additional understanding will be critical in the wake of rapid climate change, where fires might become more widespread, frequent, and intense (Cary *et al.* 2012).

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## Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

**Methods:** Deriving the Forest Fire Danger Index, and variables used in the analysis

**Table S1:** Fire severity classes and descriptions

**Table S2:** Input variables attributed to the 633 randomly selected sites that were used for the analysis

**Figure S1**: Comparative Weather Conditions and Forest Fire Danger Index for the Kilmore Gap, Coldstream, and Eildon Fire Tower weather stations.

**Figure S2:** Subregion R1 (Mount Disappointment) showing fire severity classes within stands of Mountain Ash forest.

**Figure S3:** Subregion R2 (Paradise Plains and Deep Creek) showing fire severity classes within stands of Mountain Ash forest.

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