Wildfire in wet sclerophyll forests: the interplay between disturbances and fuel dynamics

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Abstract. There are multiple pathways for vegetation to change following disturbances. Understanding those post-disturbance pathways is critical for managing wildfire risk since vegetation is fuel in a wildfire context. Across forest systems, there is considerable debate about disturbance-related changes to fuels and flammability. This study investigated post-disturbance fuel trajectories following three disturbance types—high severity wildfire, low severity wildfire, and clear-fell logging. Fuels were measured in a chronosequence of 141 sites in Mountain Ash (Eucalyptus regnans)-dominated wet sclerophyll forest in southeastern Australia, a particularly contentious forest system. Wildfires are an important part of the lifecycle of these forests, but too frequent fire can threaten post-fire regeneration. Large wildfires (in 2009, 1983 and 1939) and ongoing public and scientific debate over clear-fell logging highlight the need to better understand post-disturbance trajectories for fuel and flammability in wet sclerophyll forests. We used empirical data to test 10, sometimes contradictory, hypotheses from the scientific literature regarding post-disturbance pathways for fuel following wildfire and logging. Only five hypotheses were supported with surface fine fuels, fuel hazard, species composition, and vertical structure driving overall differences in post-disturbance fuel trajectories. The implications for flammability remain uncertain because the independent and interactive effects of many fuel components on overall flammability remain unquantified. Importantly, we found there were always high quantities of fuel, irrespective of disturbance history, which demonstrates that fire occurrence is not fuel-limited in wet sclerophyll forests. Under conditions of abundant fuel, fuel moisture could become critical to fire occurrence. Therefore, forest management should prioritize efforts to quantify not only the importance of individual fuel components to flammability but also fuel moisture dynamics in wet sclerophyll forests. As the climate (and fuels) becomes drier under climate change, it will be a major challenge to manage fire regimes in these highly valued forests.

Key words: disturbance; fire behavior; fire ecology; fire regime; flammability; forest management; fuel; logging; moist forest; Mountain Ash; wet forest; wildfire.

INTRODUCTION

Forest ecosystems are managed to provide a diverse range of services that sustain humans and wildlife (FAO 2016). Natural and anthropogenic disturbances, for example, fire, disease, insect attack, timber harvesting, and land clearing, are a fundamental concern of management as they can alter the extent to which forests deliver ecosystem services over the short and longer term. Disturbances alter the ecological properties and processes of forests, which can further
influence natural disturbance regimes (Attiwill 1994, Bengtsson et al. 2000, Bergeron et al. 2001, Ryan 2002).

Forest disturbances can alter fire regimes if they affect vegetation structure and species composition. Vegetation is the fuel in the context of a forest fire and plays a primary role in determining the flammability of a forest (i.e., its capacity to burn) and the nature of fire in a landscape (Keane 2015, Pausas et al. 2017). Examples of disturbances altering forest flammability and fire regimes include selective logging in tropical forests, which reduces canopy cover causing the forest to dry out more quickly, making it more susceptible to fire (Uhl and Kauffman 1990, Holdsworth and Uhl 1997). Outbreaks of bark beetles in North America cause widespread tree mortality, which alters the fuel structure and moisture content, making the forest more susceptible to large, high-intensity fires (Jenkins et al. 2014). The active exclusion of fire can also alter fire regimes. For example, fire suppression in North America has successfully reduced fire frequency but inadvertently increased fuel loads and thus fire severity in some forest types (Steel et al. 2015). Understanding how disturbance regimes influence fire regimes is necessary to minimize risks posed by wildfire. Specifically, we need to quantify how fuels and forest flammability will change over time as the forest responds to a range of disturbances.

Post-disturbance pathways for vegetation are highly variable, depending on the nature of the disturbance, ecology of the forest, forest condition at the time of disturbance, and climatic conditions in the post-disturbance period (Keane 2015). McCarthy et al. (2001) presented a series of theoretical post-disturbance flammability pathways based on the assumption that flammability is synonymous with the quantity of fuel in most ecosystems. The most widely applied of those is the Olson model, which predicts increasing amounts of fuel after a disturbance until an asymptote is reached ( Olson 1963). Strong support for this model, or variants of it, exists for surface fine fuels (Walker 1981, Keane 2015). However, forest flammability is likely to depend on a range of fuel attributes, not just the amount of fuel. Other fuel attributes include species composition, fuel moisture, fuel bulk density, proportion dead, and plant architecture (Gill and Zylstra 2005, Pausas et al. 2017). Empirical data to support post-disturbance models for other fuel attributes are lacking, meaning that critical parts of the fuel complex within a forest type or across the landscape are poorly quantified, thereby reducing our ability to accurately predict fire risk (Cruz and Alexander 2013).

There has been considerable debate about disturbance-related changes in flammability in the Mountain Ash (Eucalyptus regnans)-dominated wet sclerophyll forests of southeastern Australia (Lindenmayer et al. 2009, 2011, Ferguson and Cheney 2011, Attiwill et al. 2014, Taylor et al. 2014a, b). These forests support infrequent, large, intense wildfires (Murphy et al. 2013) that have resulted in major losses of life and property (Griffiths 2001, Cruz et al. 2012, Blanchi et al. 2014). They store more carbon per hectare than any other forest type in Australia (Grierson et al. 1992, Keith et al. 2009) and supply more than 50% of Victoria’s total wood volume from native forest ( VicForests 2017). They supply 80% of the catchment streamflow used as drinking water in Melbourne (Benyon and Lane 2013) and provide habitat to a range of common and threatened species including the endangered leadbeater’s possum ( Gymnobelideus leadbeateri; Lindenmayer et al. 2015).

Infrequent and intense wildfires are part of the natural lifecycle of Mountain Ash forests (Ashton 1981, Ashton and Attiwill 1994). The trees are usually killed during intense fires and regenerate from seed (Ashton 1976). As the forest regrows over many decades, the structure of the vegetation changes dramatically and can become cool temperate rainforest in more sheltered topographic positions in the absence of fire for hundreds of years (Ashton 2000, Serong and Lill 2008). Fire intervals less than 25–30 yr can eliminate Mountain Ash from the ecosystem if they are unable to reach maturity and set seed in this period (Ashton 1981, Florence 1996). Large wildfires in Mountain Ash forest (in 2009, 1983 and 1939) and ongoing public and scientific debate over clear-fell logging have accentuated the need to understand the post-disturbance pathway for fuels and flammability in Mountain Ash forests.

Several hypotheses have been proposed about how fuels and flammability in wet sclerophyll
Table 1. Summary of hypotheses relating to fuels and flammability in Mountain Ash forests.

| Component of fuel complex | Fuel-related hypothesis                                                                 | Authors referring to this fuel trait                                                                 | Inferred implications for flammability                                                                 |
|---------------------------|-----------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|
| Surface fine fuels        | (1a) The quantity of surface fine fuel is highest in stands aged approximately 40 yr   | Ashton (1975); Florence (1996:73)                                                                     | Flammability is highest in stands approximately 40 yr old                                               |
|                           | (1b) Surface fine fuels accumulate according to a modified exponential curve, increasing rapidly to an equilibrium | Mackey et al. (2002 p. 30); McCaw et al. (2002) in Karri (E. diversicolor) forest; Polglase and Attiwill (1992); Sitters et al. (2014) | Flammability increases with time since fire up to an equilibrium level                                   |
| Elevated fine fuels       | (2a) The density of elevated fine fuels peaks in young stands and subsequently declines with time since fire | Bowman et al. (2014); Florence (1996:68); Lindenmayer et al. (2009, 2011)                            | Flammability is highest in young stands and then declines with time since fire                          |
|                           | (2b) Regular low severity (surface) fires may maintain a more open understorey         | Ashton (1981); Attiwill (1994); Florence (1996:67)                                                   | Flammability is less in areas burnt frequently by low severity fire                                     |
|                           | (2c) The proportion of dead, elevated fuel will peak at about 30 yr post-disturbance and subsequently decline | McCaw et al. (2002) in Karri (E. diversicolor) forest                                                 | Flammability will peak at 30 yr post-disturbance and then subsequently decline                           |
| Fuel hazard               | (3) The overall fuel hazard increases post-disturbance up to an equilibrium level      | In dry eucalypt forest: Gould et al. (2011); Duff et al. (2012)                                       | Flammability increases with time since fire up to an equilibrium level                                   |
| Understorey species       | (4a) The abundance of mesic species in the understorey increases with time since fire  | Ashton (1976); Barker (1991); McCarthy et al. (2001); Serong and Lill (2008)                      | Flammability is less in older forests where there are more mesic species                               |
| composition               | (4b) Logging shifts the species composition to one more characteristic of drier forests | Lindenmayer et al. (2009); Lindenmayer (2009); Taylor et al. (2014b); Mueck and Peacock (1992)     | Flammability is greater in logged forests due to a higher abundance of species more typical of dry eucalypt forests |
| Vertical structure        | (5) The vertical distances between fuel strata are less in younger forests              | Lindenmayer et al. (2011); Mackey et al. (2002:32); Taylor et al. (2014b); Serong and Lill (2008)    | Wildfires are more likely to crown in younger stands because there is a smaller vertical distance between fuel strata |
| Fallen logs               | (6) Older stands contain more large fallen logs that act as a substrate for luxuriant moss mats | Lindenmayer (2009); Lindenmayer et al. (2011)                                                        | Flammability is less in forests with large logs because they act as micro-firebreaks reducing the spread of surface fires and moss mats on large logs retain moisture |

Forest change following disturbance (Table 1). The hypotheses consider five different characteristics of the fuel complex: surface fine fuel, elevated fine fuel, species composition, vertical structure, and fallen logs. Some of the hypotheses are contradictory, and there has been a lack of empirical data to test them. Our study sought to quantify the effects of fire history and logging on fuels in Mountain Ash-dominated wet sclerophyll forests using a chrono-sequence of 141 sites. Specifically, we asked which, if any, of the 10 proposed fuel hypotheses (Table 1) were supported by empirical data. In doing so, we quantified how different fuel characteristics change following time since wildfire and logging.

**Methods**

**Site selection**

The study was undertaken in Mountain Ash (*Eucalyptus regnans*) forest in the Central Highlands region of Victoria in Australia (Fig. 1). Mountain Ash forests are endemic to southeastern Australia (the States of Victoria and Tasmania) and occur where there is high, relatively reliable rainfall (typically exceeding 1000 mm/yr) and deep, fertile soils (Ashton and Attiwill 1994). The Central Highlands region of Victoria has been impacted by several major wildfires over the last 100 yr, including fires in 1939, 1983, and 2009 (Collins 2009). Clear-fell logging has also been...
common practice in these forests since the early 1980s (Florence 1996). Selective harvesting practices typically occurred before that time (Griffiths 2001).

We stratified the landscape by disturbance type (wildfire, logging, long unburnt, and no recent history of logging), time since disturbance, aridity, and fire severity (only mapped for the 2009 fire; Appendix S2: Table S1). We then used a randomization process to select candidate plot locations within each stratification unit. Aridity index (Nyman et al. 2014) was used as a surrogate for topographic position, with the aim to capture a similar range of aridity indices for each disturbance class. Fire severity maps for the 2009 wildfire areas (Department of Environment Land Water and Planning 2009) were used to select sites in both high and low fire severity areas, though the final fire severity classification for each site was based on tree diameters and fire history records (further details in Data analysis section below). Sites were all within 50–150 m of a road for accessibility and at least 500 m apart if they had shared disturbance histories. Sites with gradients exceeding 30 degrees were deemed too steep to work in safely and omitted from the study. A total of 200 candidate sites were created, of which 141 were surveyed in the field. Table 2 outlines the 10 different disturbance classes and the sample sizes for each disturbance class.

Field measurements
At each site, we marked out a 400-m² square plot and two 50 m long transects. All measurements occurred either within the 400-m² plot (species diversity), using a variable radius plot from the northeast plot corner (trees), from all four plot corners (fine fuels) or along the transects (coarse woody debris).
Fuel at each site was measured in autumn 2016 (April–June) to test the 10 fuel hypotheses (Table 1). To avoid inconsistent results between different assessors (Watson et al. 2012), fuels were assessed by the same pair of assessors for all sites. Surface, near surface, and elevated fuel (as defined by Hines et al. 2010, Gould et al. 2011) were assessed within a 5 m radius of each of the four plot corners of the main 400-m² plot. Surface fine fuels were quantified by measuring the litter depth four times at each plot corner using a fuel depth gauge and estimating the percent cover of litter. Near surface and elevated fine fuel were assessed by estimating percent cover, height, and proportion dead. Near surface fine fuel is live and dead vegetation effectively in touch with the ground and typically less than 0.5 m high. Elevated fine fuel is generally upright vegetation (typically 0.5–2 m high) with a clear gap between the ground and the plant. Cover of near surface and elevated fuel were combined for some of the analysis, resulting in some cover percentages more than 100%.

Fuel hazard scores were assigned for each site using the descriptors in the Overall Fuel Hazard Guide (Hines et al. 2010). Surface hazard is based on litter depth and cover. Measurements from the four plot corners were averaged and those averages used to determine the surface hazard for the site. Near surface and elevated hazard are based on percent cover, proportion dead, and the height of fuel. Once again, measurements were averaged for each plot corner and those averages used to determine the near surface and elevated hazard for the site. Bark fuel hazard was assessed visually across the site using photos and descriptions provided in the Overall Fuel Hazard Guide (Hines et al. 2010), which considers bark type (e.g., fine fibrous, ribbon, smooth, papery), amount of loosely held bark, and degree of bark char from past fires. Scores for each fuel strata were combined, as per the tables in the Hazard Guide, to give an overall fuel hazard score for the site (Hines et al. 2010). For analysis, the overall fuel hazard score was converted from ordinal categories (low, medium, high, very high, extreme) to numerical values (1–5).

Fuel load was not measured directly; however, fuel hazard arguably better reflects flammability than fuel load because it considers several different fuel attributes, not just the total amount. In our analysis and interpretation of results, we assumed fuel hazard, elevated cover, and litter depth accumulate similarly to fuel load (as demonstrated by Tolhurst and Kelly 2003, Gould et al. 2011). Species diversity was measured using time-limited surveys (30 min) to identify all the species with 400-m² square plots. Time-limited surveys may overlook minor components of the vegetation community; however, these are unlikely to have a measurable impact on fire behavior. For each species, we took a visual estimate of cover (nearest 10%) and the average top height and bottom height of the foliage. The cover data for each species were used to determine the abundance of ferns and dry forest species. The foliage heights were used to calculate the vertical distances between the understorey and canopy fuels.

Table 2. Disturbance classes used in the analysis and the number of plots within each class.

| Disturbance class | Type of disturbance | Year of last disturbance | Time since disturbance (years) | n  |
|-------------------|---------------------|--------------------------|-------------------------------|----|
| High severity 7 yr| High severity wildfire| 2009                     | 7                             | 8  |
| High severity 33 yr| High severity wildfire| 1983                     | 33                            | 3  |
| High severity 77 yr| Low severity wildfire| 1939                     | 77                            | 21 |
| Low severity 7 yr | Low severity wildfire| 2009                     | 7                             | 30 |
| Low severity 33 yr| Low severity wildfire| 1983                     | 33                            | 17 |
| Low severity 77 yr| Low severity wildfire| 1939                     | 77                            | 13 |
| Logging 6–16 yr   | Clear-fell logging  | 2000–2010                | 6–16                          | 27 |
| Logging 17–26 yr  | Clear-fell logging  | 1990–1999                | 17–26                         | 13 |
| Logging 27–36 yr  | Clear-fell logging  | 1980–1989                | 27–36                         | 6  |
| Long unburnt      | Long unburnt        | 1825–1875†               | 100+                          | 3  |

† Estimated using measured tree diameters and equations provided by Ashton (1976).
Coarse woody debris was assessed along two 50-m transects using a line-intersect approach. One transect was oriented downslope and the other across slope. We recorded log diameter and decay class (as per Lindenmayer et al. 1999) for all intersecting logs with diameters exceeding 10 cm.

Additionally, to help determine the fire history we measured the 12 closest trees from the northeast plot corner (up to a maximum distance of 20 m). For each tree, we recorded the distance to plot corner, species, diameter at 1.3 m and estimated cohort.

Data analysis
Sites were grouped by disturbance history using the mapped disturbance histories and tree measurements from within the plots (Table 2). Measured tree diameters were used to estimate tree age (as per Ashton 1976). For wildfire burnt sites, fire severity was estimated from the mapped time since last fire and tree ages. If more than 70% of trees appeared to have regenerated following the last fire (based on the calculated tree ages), then the last fire severity was classified as high. Otherwise the fire severity was classified as low. Similar approaches have been used by Ough (2001), Lindenmayer (2009), and Cawson et al. (2017). This post hoc approach for classifying fire severity explains the unbalanced number of plots within each disturbance class. Mapped fire severity was also used as a guide but was only available for the 2009 fires.

The same analysis methods were used for all fuel components to test differences between the disturbance history classes. We derived eight fuel response variables from the field data, as defined in Table 3. One-way ANOVAs were used to test the significance of differences between disturbance classes for each fuel response variable. Where the data were not normally distributed (as determined using a Shapiro test) or where the variances were unequal (as determined using a Bartlett test), a Kruskal–Wallis test was used instead of a one-way ANOVA. Following a statistically significant test result ($P < 0.05$), paired comparisons were made (Tukey HSD test for normal data or Wilcox test for non-normal data) to identify pairs that were statistically significantly different. All analysis was done in R statistical software version 3.3.2 (R Core Team 2016).

Table 3. Fuel response variables derived from the field data.

| Fuel response variable | Units | Definition |
|------------------------|-------|------------|
| Litter depth          | mm    | Mean depth of litter taken from 16 measurements per plot |
| Near surface and      | %     | Mean percent cover from four measurements per plot. Near surface and elevated covers were assessed separately and then summed together, sometimes giving values exceeding 100% |
| elevated fine fuel cover |    | |
| Dead, elevated fine fuel | %  | Mean proportion of dead fine fuel from four measurements per plot |
| Overall fuel hazard    | –     | Score from 1 to 5 as per the Overall Fuel Hazard Guide |
| Dominance of ferns     | %     | The total cover of all fern species divided by the total cover for all understorey and mid-storey species |
| Dominance of dry forest species | % | The total cover of all dry forest species divided by the total cover for all species. Only understorey and mid-storey species considered |
| Vertical gap           | m     | The total vertical distance between the foliage in each vegetation strata. The mid-storey was only included if its total cover exceeded 20%. Input data were cover, top and bottom heights estimated for every species. Mean values were used for foliage heights |
| Log diameter           | cm    | Mean diameter of all logs (exceeding 10 cm in diameter) that intersected the transects |
RESULTS

Overall, our data supported five of the 10 fuel hypotheses (Table 4). Those supported related to surface fuels (hypothesis 1b), overall fuel hazard, understorey species composition, and vertical structure. Those not supported related surface fuels (hypothesis 1a), elevated fine fuels, and fallen logs.

Surface fine fuel depths for individual disturbance histories ranged from 28 mm (standard deviation [SD] 10 mm) to 78 mm (SD 25 mm) with an overall mean of 44 mm (SD 18 mm) (Fig. 2; Appendix S2: Table S1). The depth of surface fuel increased significantly with time since high severity wildfire (Appendix S2: Table S2; \( P = 0.002 \)) and low severity wildfire (Appendix S2: Table S2; \( P = 0.013 \)). There were insufficient time increments to fit a modified exponential curve (i.e., Olson model) but the median fuel depths as a function of time since fire visually fit the shape of this model. There were no significant differences in fuel depth between the age classes for the logged sites, although the oldest sites were only 36 yr post-logging (Appendix S2: Table S2; \( P = 0.917 \)). In the most recently disturbed sites, depths were significantly higher for low fire severity plots compared with high fire severity and logged plots (Appendix S2: Table S3; \( P = 0.001 \)). There were no significant differences in depths between disturbance types for the older plots (Appendix S2: Table S3; \( P = 0.414 \) and 0.075 for 27–36 yr and 77+ yr, respectively).

Near surface and elevated fine fuel cover (near surface + elevated) for individual disturbance histories ranged from 69% (SD 25%) to 101% (SD 25%) with an overall mean cover of 92% (SD 26%; Fig. 3; Appendix S2: Table S1). There were no significant differences in cover between times since disturbance (Appendix S2: Table S2; \( P = 0.465, 0.100, 0.051 \) for high fire severity, low fire severity, and logging, respectively) or disturbance types (Appendix S2: Table S3; \( P = 0.734, 0.478, 0.628 \) for 6–16 yr, 27–36 yr, and 77+ yr, respectively).

The proportion of dead, elevated fine fuel for individual disturbance histories ranged from 11% (SD 5%) to 35% (SD 20%) with an overall mean of 16% (SD 10%; Fig. 4; Appendix S2: Table S1). Significant differences in the proportion of dead, elevated fuels were found between the most recently disturbed (6–16 yr) and older (27–36 yr) logged sites (Appendix S2: Table S2; \( P = 0.008 \)), with a higher proportion of dead, elevated fuels in the younger sites. The proportion of dead, elevated fuels was significantly higher in the 6- to 16-yr-old logged plots compared with the 7-yr-old wildfire sites (Appendix S2: Table S3; \( P = 0.006 \)). The mean proportion of dead, elevated fuels was relatively high for long unburnt (35%) but not statistically significantly higher than the other times since high severity wildfire (Appendix S2: Table S2; \( P = 0.117 \)).

Overall fuel hazard scores for individual disturbance histories ranged from 3.1 (SD 0.8) to 5 (SD 0) with an overall mean of 3.9 (SD 0.9; Table S3; \( P = 0.917 \)).

Table 4. Summary of results in relation to the fuel hypotheses in Mountain Ash forests.

| Component of fuel complex | Fuel-related hypothesis | Evidence in support of hypothesis |
|---------------------------|-------------------------|----------------------------------|
| Surface fine fuels        | (1a) The quantity of surface fine fuel is highest in stands aged approximately 40 yr | No |
|                           | (1b) Surface fine fuels accumulate according to a modified exponential curve, increasing rapidly to an equilibrium | Yes |
| Near surface and          | (2a) The density of elevated fine fuels peaks in young stands and subsequently declines with time since fire | No |
| elevated fine fuels       | (2b) Regular low severity (surface) fires may maintain a more open understorey | No |
|                           | (2c) The proportion of dead, elevated fuel will peak at about 30 yr post-disturbance and subsequently decline | No |
| Overall fuel hazard       | (3) The overall fuel hazard increases post-disturbance up to an equilibrium level | Yes |
| Understorey species       | (4a) The abundance of mesic species in the understorey increases with time since fire | Yes |
| composition               | (4b) Logging shifts the species composition to one more characteristic of drier forests | Yes |
| Vertical structure        | (5) The vertical distances between fuel strata are less in younger forests | Yes |
| Fallen logs               | (6) Older stands contain more large fallen logs that act as a substrate for luxuriant moss mats | No |
Significant differences in hazard were found between the most recently disturbed (7 yr) and older (77 and 100+ yr) high fire severity sites (Appendix S2: Table S2; $P = 0.006$), with a lower hazard score in the younger sites. Hazard scores were higher following low fire severity compared with high severity wildfire (7 yr post-burn), but those differences were not statistically significant (Appendix S2: Table S3; $P = 0.082$). There were no significant differences between times or disturbances.

Fig. 2. Boxplots showing surface fine fuel depth as a function of time since disturbance and disturbance type. a) High severity fire, b) Low severity fire, and c) Logging. Lower case letters denote the results of significance testing between times within the same disturbance type; if the letters are different, then there is a statistically significant difference ($P < 0.05$). Upper case letters denote the results of significance testing between disturbances types within the same time increment.

Fig. 3. Boxplots showing cover of near surface and elevated fine fuel as a function of time since disturbance and disturbance type. a) High severity fire, b) Low severity fire, and c) Logging. Values exceed 100% because they represent the sum of cover within two vegetation strata (near surface + elevated). Lower case letters denote the results of significance testing between times within the same disturbance type; if the letters are different, then there is a statistically significant difference ($P < 0.05$). Upper case letters denote the results of significance testing between disturbances types within the same time increment. Significance testing found no significant differences between times or disturbances.
no significant differences in hazard between the logged and high severity wildfire sites.

Fern cover for individual disturbance histories ranged from 6% (SD 7%) to 62% (SD 8%) with an overall mean of 25% (SD 25%; Fig. 6; Appendix S2: Table S1). The dominance of ferns increased with time since disturbance, although statistically significant increases in fern abundance only occurred following high severity (Appendix S2: Table S2; $P = 0.048$) and low severity ($P = 0.005$) wildfire, not logging ($P = 0.289$). Ferns were more dominant in the wildfire than the logged sites for the most recently disturbed sites (Appendix S2: Table S3; $P = 0.002$) but not the older sites. Differences in the dominance of ferns between the high and

![Boxplots showing proportion (%) of elevated fine fuel that was dead as a function of time since disturbance and disturbance type.](image)

**Fig. 4.** Boxplots showing proportion (%) of elevated fine fuel that was dead as a function of time since disturbance and disturbance type. a) High severity fire, b) Low severity fire, and c) Logging. Lower case letters denote the results of significance testing between times within the same disturbance type; if the letters are different, then there is a statistically significant difference ($P < 0.05$). Upper case letters denote the results of significance testing between disturbances types within the same time increment.

![Boxplots showing overall fuel hazard score as a function of time since disturbance and disturbance type.](image)

**Fig. 5.** Boxplots showing overall fuel hazard score as a function of time since disturbance and disturbance type. a) High severity fire, b) Low severity fire, and c) Logging. Lower case letters denote the results of significance testing between times within the same disturbance type; if the letters are different, then there is a statistically significant difference ($P < 0.05$). Upper case letters denote the results of significance testing between disturbances types within the same time increment.
low severity wildfire sites were non-significant ($P > 0.05$).

Cover of dry species for individual disturbance histories was low overall, ranging from 0% (SD 0%) to 7% (SD 12%) with an overall mean of 2% (SD 5.8%; Fig. 7; Appendix S2: Table S1). The dominance of drier species declined with time since disturbance in the low and high fire severity sites (Appendix S2: Table S2; $P = 0.033$). The dominance of drier species was significantly higher 6–16 yr post-disturbance in low severity wildfire and logging compared with high severity wildfire (Appendix S2: Table S3; $P = 0.040$ for 6–16 yr post-disturbance).

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**Fig. 6.** Boxplots showing proportion (%) of total understorey cover that consisted of fern species as a function of time since disturbance and disturbance type. a) High fire severity, b) Low fire severity, and c) Logging. Lower case letters denote the results of significance testing between times within the same disturbance type; if the letters are different, then there is a statistically significant difference ($P < 0.05$). Upper case letters denote the results of significance testing between disturbances types within the same time increment.

**Fig. 7.** Boxplots showing proportion (%) of total understorey cover that consisted of species more typical of dry forests as a function of time since disturbance and disturbance type. a) High fire severity, b) Low fire severity, and c) Logging. Lower case letters denote the results of significance testing between times within the same disturbance type; if the letters are different, then there is a statistically significant difference ($P < 0.05$). Upper case letters denote the results of significance testing between disturbances types within the same time increment.
Vertical distance between strata for individual disturbance histories ranged from 4 m (SD 1 m) to 32 m (SD 15 m; Fig. 8; Appendix S2: Table S1). Typically, the vertical distance increased significantly with time since disturbance for the high fire severity (Appendix S2: Table S2; $P = 0.0001$) and logged sites (Appendix S2: Table S2; $P = 0.006$). An exception to this was the long unburnt sites, which had smaller vertical distances on average than the 33- and 77-yr-old sites. There was no significant difference in vertical distance between the long unburnt (100+ yr) sites and 7-yr-old sites (pairwise comparison; $P > 0.05$). There were no significant differences in log diameter between the disturbance types, with the exception of logging and low severity fire at 27–36 yr post-disturbance (Appendix S2: Table S3; $P = 0.006$). Larger diameter logs (outliers on the boxplots in Fig. 9) did not appear to occur more frequently in the older sites.

**DISCUSSION**

*Evaluation of the fuel hypotheses*

Our empirical data only support five of the 10 fuel-related hypotheses proposed by earlier studies (Table 4). Those supported relate to surface fuel, fuel hazard, species composition, and vertical structure. The large number of unsupported hypotheses indicates that despite the large body of research about the ecology and silviculture of these forests (e.g., Attiwill 1994, Ashton 2000, Lindenmayer et al. 2015), there is a lack of understanding about post-disturbance pathways for fuel in Mountain Ash forests. Our analysis goes some way toward addressing that knowledge gap by providing new insights into fuel dynamics following disturbances in Mountain Ash forests.

Surface fine fuels accumulated rapidly before reaching an equilibrium, supporting hypothesis 1b but contradicting 1a. There were insufficient
time increments in our data to fit a modified exponential curve (Olson 1963), but visually they approximated one. The lack of time increments is one challenge of chrono-sequence research in forests that burn infrequently. Overall, litter depths were high at all the measured time increments (ranging from 28 to 78 mm), above the 25 mm threshold when litter fuel is deemed a very high to extreme hazard (Gould et al. 2007, Hines et al. 2010). Similarly, Ashton (1975) reported deep litter in Mountain Ash forest, ranging from 20 to 90 mm in more open sections of forest and 150–180 mm in denser, ferny areas. In contrast, mean litter depths for long unburnt were 33 mm in mixed-species eucalypt forest (E. obliqua, E. rubida and E. radiata) (Tolhurst and Kelly 2003) and 24–27 mm in Jarrah forest (E. marginata) with low and tall shrubs, respectively (Gould et al. 2011). Deeper litter in low fire severity compared with high fire severity at 7 yr post-fire (17 mm deeper) probably reflected the intact mature canopy in low fire severity compared with regenerating forest in high fire severity; subsequently, for 33 and 77 yr post-fire there were no significant differences in litter depth between the fire severities. Surface fuels have been found to influence both the rate of spread in dry eucalypt forests under some conditions (McArthur 1968, Gould et al. 2007), yet their importance to fire behavior and flammability in wet sclerophyll forests has not been formally quantified.

Fuel hazard increased with time since fire up to an equilibrium level (hypothesis 3), although the rate of accumulation varied with fire severity. High severity wildfire sites reached extreme hazard levels by about 77 yr on average. Fuel hazard accumulation rates for Mountain Ash forests are not reported elsewhere, but in dry eucalypt forests, fuel hazards are reported to follow a similar trajectory post-fire (Gould et al. 2011, Duff et al. 2012). Fuel hazard levels reached extreme levels more quickly (within 33 yr) in the low fire severity sites possibly because significant amounts of fuel were retained post-fire, especially bark fuel. A limitation with fuel hazard assessment methods is the small number of hazard classes, particularly at the higher levels of fuel hazard, which makes it difficult to distinguish between sites with higher levels of fuel. This means many sites are assigned the same hazard class when there are substantial differences in the amount of fuel and likely fire behavior.

Abundance of mesic species increased with time since fire (hypothesis 4a); this has also been reported elsewhere (Ashton 1976, Lindenmayer et al. 2000, Serong and Lill 2008). In comparing different disturbance types, ferns were significantly more abundant in the high
severity wildfire than the logged sites, which concurs with the findings of other studies in Mountain Ash forests (Ough 2001, Serong and Lill 2008, Blair et al. 2016). Soil disturbance during the clear-felling operation is thought to damage propagules for resprouting species including ferns (Ough 2001). Ferns and other mesic species are thought to reduce forest flammability (McCarthy et al. 2001), but the magnitude of their effects nor their mechanisms for influencing flammability have not been formally quantified.

Species more typical of dry forests were more abundant in logged compared with high severity wildfire sites in younger stands (hypothesis 4b), but subsequently, for older stands differences between logging and high severity wildfire were not statistically significant. Mueck and Peacock (1992) reported a shift in species composition following logging toward drier species, but their sampling design and analysis have been contested (Attiwill et al. 2014). Ough (2001) reported differences in species composition between logging and wildfire but did not consider the flammability implications. Overall, dry species abundances were very low (averaging 2%), suggesting these species are unlikely to drive forest flammability despite shifts in abundances. If species trait information had been available, then it may have been more informative to examine relative abundances of different plant traits, for example, hot versus fast flammable traits (Pausas et al. 2017).

Vertical distances between fuel strata were less in younger forests (hypothesis 5), reflecting shorter saplings in younger forest compared with tall trees in mature forest. Serong and Lill (2008) also measured vertical distances and their results concur with ours. Vertical distances were much larger (averaging 28 m larger) following low severity wildfire compared with high severity wildfire or logging because a mature tree canopy remained post-fire in low fire severity. The size of vertical gaps is likely to influence the propensity for crown fire with crown fires occurring more often in younger wet sclerophyll forests where the vertical gap is smaller (Taylor et al. 2014b).

Cover of near surface and elevated fine fuel was consistently high (greater than 71%) irrespective of the time since disturbance and disturbance type. These results were contradictory to hypotheses 2a and 2b. Hypothesis 2a assumed that as the dense, young Mountain Ash grew taller and were no longer within the elevated fuel strata that the elevated fuel strata would become less dense (as described by Lindenmayer et al. 2009, 2011). However, our data show that the cover of near surface and elevated fuels remains high due to the many understory species. Hypothesis 2b assumed that wet forests were akin to dry forests with regular, low severity fires maintaining a more open understory (Attiwill 1994). Our study only measured the effects of one low severity fire, rather than consecutive fires. However, the data showed that changes to the understory following a low severity fire were short-lived, with new growth quickly filling any space made by the fire.

The proportion of dead, elevated fuel was relatively low (17% on average), irrespective of disturbance history, which is contradictory to hypothesis 2c. The proportion of dead, elevated fuels peaked at about 30 yr in Karri forests, a type of wet sclerophyll forest occurring in Western Australia (McCaw et al. 2002). The absence of a similar scenario in Mountain Ash forests could reflect differences in climatic conditions and thus decomposition rates of these two forest types or other differences in the lifecycles of the understory species. Low levels of dead material within the elevated fuel of Mountain Ash forest mean it is unlikely to have a major impact on fuel hazard and flammability (Hines et al. 2010). However, our measurements only represent one point in time, during a wet year whereas the proportion of dead, elevated fuels is likely to vary seasonally and between years. It is likely that the dead component would be higher in summer, particularly under drought conditions (Ashton 1976, Ashton and Attiwill 1994) when Mountain Ash forests burn.

Older stands do not contain more large fallen logs. Mean log diameters did not change with time since high severity wildfire, with diameters ranging from 20 to 25 cm. In contrast, Lindenmayer et al. (1999) detected a significant difference in log diameter between younger and older stands, though the absolute difference was small and differences in log volume were non-significant. Turner et al. (2011) found no significant difference in percent cover of logs between age
classes in wet eucalypt forest in Tasmania. Log diameters were significantly smaller for logged compared with wildfire sites at 27–36 yr post-disturbance (16 cm vs. 20 cm for logging and high fire severity, respectively), possibly because there were far fewer retained dead standing trees in the logged sites.

**Linking fuel to flammability**

Understanding fuel dynamics is a first step toward understanding post-disturbance flammability pathways. Our study identified multiple post-disturbance fuel pathways, which vary as a function of disturbance and fuel type. Yet, the implications for flammability remain uncertain because for many fuel components, their effects on flammability have not been quantified. Moreover, for all fuel components little is known about how they interact to have a combined effect on overall flammability.

In Mountain Ash forests, surface fine fuels, species composition (ferns and dry species abundance), and vertical gaps changed significantly with time since disturbance and between disturbance types. Therefore, those fuel components appear to drive differences in fuel overall along post-disturbance pathways. Using two of those fuel components—surface fine fuels and fern abundance—we can illustrate the challenges with drawing broader conclusions about forest flammability. Surface fine fuels are frequently implicated to affect fuel availability and rate of spread—as the quantity of (dry) surface fine fuel increases, so too does fuel availability, resulting in more intense fire behavior (Walker 1981, Pyne 1996) and increased rates of spread at low wind speeds (Burrows 1999a, b, Gould et al. 2007). Consequently, we might expect forest flammability to increase with time since disturbance as litter depth increases. However, counteracting those deeper litter beds is an increased abundance of ferns, which are thought to reduce flammability. The deepest litter beds often occur where fern cover is most dense (Ashton 1975).

There is a paucity of research linking ferns to flammability, but landscape analyses show associations between mesic species and less intense fire behavior (Wood et al. 2011, Leonard et al. 2014). Therefore, it appears that litter depth and fern abundance have opposing effects on flammability. There is no simple means to bring these two fuel components together to determine an overall flammability outcome.

Irrespective of how the individual fuel components contribute to the overall flammability of the forest, one distinct feature of the data was the very large amount of fuel. At no time in our chrono-sequence of measurements would the amount of fuel limit the spread of fire. Yet despite large amounts of fuel, wildfires are infrequent in wet sclerophyll forests, consistent with other wet forest ecosystems (Meyn et al. 2007, Bradstock 2010, Krawchuk and Moritz 2011). High fuel moisture contents make the fuel largely unavailable to burn despite its abundance in wet sclerophyll forests; that fuel availability can vary as a function of canopy cover and disturbance history (Cawson et al. 2017). Therefore, to quantify the flammability of wet sclerophyll forests, efforts should be directed toward quantifying not only the role of individual fuel components but also fuel moisture dynamics.

In the longer term, a drying climate in this region with the onset climate change threatens the long-term viability of these forests. Reduced rainfall and a larger number of extreme fire days (Flannigan et al. 2009, Bradstock 2010) could make wet sclerophyll forests drier and thus available to burn more often. Higher frequency fires could eliminate the eucalypts from the ecosystem since they require at least 25–30 yr between fires to reach maturity and set seed (Bowman et al. 2014). Vast tracts of wet sclerophyll forests could be transformed to forests dominated predominately by *Acacia* species, which would have negative implications for important ecological functions such as the formation of tree hollows and carbon storage (Lindenmayer et al. 2011, Bowman et al. 2014). Understanding fuel dynamics following disturbances will be critical for managing fire regimes in these highly valued forests under climate change.

**Conclusion**

We tested 10 fuel hypotheses regarding post-disturbance pathways for fuel in Mountain Ash-dominated wet sclerophyll forest. Only five hypotheses were supported by our empirical data. Our results show that surface fine fuels, fuel hazard, species composition, and vertical structure drive overall differences in post-disturbance
fuel trajectories. The implications for flammability remain uncertain because for many fuel components, their effects on flammability have not been quantified. Moreover, for all fuel components little is known about how they interact to have a combined effect on overall flammability.

Importantly, there appeared to always be high quantities of fuel, irrespective of disturbance history, which demonstrates that fire occurrence is not fuel-limited in wet sclerophyll forests. Under conditions of abundant fuel, fuel moisture is likely to be critical to fire occurrence. This has implications for forest management both now and in the future. Management should prioritize efforts to quantify not only the role of individual fuel components to flammability but also fuel moisture dynamics in wet sclerophyll forests to enable better predictions of wildfire risk. Under climate change, a drier climate could make the fuels in wet sclerophyll forests available to burn more frequently. This poses a major challenge for forest managers as too frequent wildfire threatens the viability of these forests.

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Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.2211/full