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Research Note

Effects of altered fire intervals on critical timber production and conservation values

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Abstract. Forests exhibit thresholds in disturbance intervals that influence sustainability of production and natural values including sawlog production, species existence and habitat attributes. Fire is a key disturbance agent in temperate forests and frequency of fire is increasing, threatening sustainability of these forest values. We used mechanistically diverse, theoretical fire interval distributions for mountain ash forest in Victoria, Australia, in the recent past and future to estimate the probability of realising: (i) minimum sawlog harvesting rotation time; (ii) canopy species maturation; and (iii) adequate habitat hollows for fauna. The likelihood of realising fire intervals exceeding these key stand age thresholds diminishes markedly for the future fire regime compared with the recent past. For example, we estimate that only one in five future fire intervals will be sufficiently long (~80 years) to grow sawlogs in this forest type, and that the probability of forests developing adequate habitat hollows (~180 years) could be as low as 0.03 (3% of fire intervals). Therefore, there is a need to rethink where sawlogs can be sourced sustainably, such as from fast-growing plantations that can be harvested and then regrown rapidly, and to reserve large areas of existing 80-year-old forest from timber harvesting.

Keywords: climate change, biodiversity, fire regime, fire frequency, trees: eucalyptus, fire interval likelihood models.

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Introduction

Forests, like all natural systems, exhibit thresholds in disturbance intervals that influence sustainability of production and natural values. Intervals between fires can determine the probability of achieving sawlog harvesting rotation times (Armstrong 2004; González *et al.* 2005; Savage *et al.* 2011; Gauthier *et al.* 2015), especially in forest types where fires are typically stand-replacing. Similarly, disturbance intervals influence sustainability of natural values, directly through canopy species maturation (Franklin *et al.* 2002; Brown and Johnstone 2012; Splawinski *et al.* 2019) or indirectly through influencing habitat requirements like tree hollows (Lindenmayer *et al.* 2017).

Here, we explore these relationships in mountain ash (*Eucalyptus regnans*) forests of the Central Highlands of Victoria, south-eastern Australia. These forests are subject to stand-replacing wildfires (Ashton, 1981) on average every ~100 years (McCarthy *et al.*, 1999). However, these forests are predicted to experience an increasing frequency and extent of fire due to climate change (Fairman *et al.* 2016), with landscape-scale, mechanistic simulation of fire dynamics – in south-eastern Australian forests more generally – indicating that intervals between fires may approximately halve by 2070 (Cary 2002; King *et al.* 2011).

Mountain ash forests are used extensively and intensively for wood production, and are harvested using conventional clearcutting on a nominal rotation of ~80 years (Flint and Fagg 2007). Conservation-related time thresholds include a 20-year maturation period for seed production by the dominant canopy species (von Takach Dukai *et al.* 2018) and at least 180 years after disturbance for the development of hollows suitable for cavity-dependent fauna (Lindenmayer *et al.* 2017).

Our key question was: what is the relationship between fire frequency (as a key fire regime variable) and the probability of forest stands reaching specific ages required for biological maturity, sawlog harvesting, and developing adequate habitat hollows in the recent past and the future? We used a range of simple, theoretical fire-interval distributions representing diverse mechanisms influencing fire occurrence in these forests (see McCarthy *et al.* 1999). Our objective was to mathematically quantify the theoretical probability of realising fire intervals at least as long as these key production and conservation stand age thresholds for the recent past and the future (2070).

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Methods

Study area

Our insights come from the mountain ash forests of the Central Highlands of Victoria, south-eastern Australia, ~120 km north-east of Melbourne. Mountain ash is the tallest flowering plant in the world, with mature trees reaching heights of ~100 m (Ashton 1975). The species occurs in high-rainfall areas (Lindenmayer *et al.* 1996), often on deep, fertile soils. Mountain ash is an obligate seeder, meaning that wildfires generally kill almost all trees, with the forest then regenerating from seed (Smith *et al.* 2014), typically creating even-aged stands of trees (Ashton 1981). The mean interval between high-intensity and high-severity fire in mountain ash forest has previously been estimated as 107 years (95% confidence limits were 45 and 333 years) (McCarthy *et al.* 1999) based on analysis of stand origins from 1750 to 1939 (Kuczera 1987). However, there have been major wildfires in various parts of the Central Highlands region in 1926, 1932, 1939, 1983 and 2009 as well as less extensive conflagrations in 1908, 1919, 1948, 2004 and 2019.

There is ~157 000 ha of mountain ash forest in the Central Highlands of Victoria and it is one of the most important timber tree species in the State (Flint and Fagg 2007) with an estimated 70% of Victorian timber and pulpwood production occurring in the region. The mountain ash estate is currently dominated by young forest and advanced regrowth forest, with 98.8% of the ecosystem in the region comprising stands ~120 years or younger and the remaining ~1.2% of forest exceeding 120 years of age (Lindenmayer *et al.* 2020).

Fire interval functions and thresholds

Our study incorporates fire interval distributions, $f(t)$, developed from three mechanistically diverse flammability or hazard functions, $h(t)$, assuming through time either: constant fire hazard (exponential function, Eqn 1); fire hazard that parallels fine, dead fuel accumulation after the previous fire (Olson function, Eqn 2); or fire hazard determined by forest understorey moisture characteristics after the previous fire (moisture function, Eqn 3) (McCarthy *et al.* 2001).

$$h(t) = h \tag{1}$$

$$h(t) = h\left(1 - e^{-kt}\right) \tag{2}$$

$$h(t) = h\left(1 - e^{-kt}\right)\left(r + e^{-mt}\right) \tag{3}$$

where h is the long-term annual probability of fire, t is time since fire (years), k is the fuel decomposition constant (unitless) of Olson (1963) and, where relevant, flammability declines to a level given by rh at a rate defined by m. We adopted parameter values for Eqns 1 to 3 estimated for mountain ash forest in O'Shannassy and Watts River Water catchments, Victoria, Australia (McCarthy *et al.* 1999). We incorporated values for h, k, r and m of 0.01, 0.12, 0.33 and 0.0035 respectively in these models for the recent past (McCarthy *et al.* 1999).

Fire interval distributions $f(t)$ are defined for each hazard function by:

$$f(t) = h(t)e^{-H(t)} \tag{4}$$

where $H(t)$ is the integral of $h(t)$ for each hazard function case (McCarthy *et al.* 2001). A probability of realising a fire interval as long as or longer than specific stand age thresholds, $1 - F(t)$, was determined from each cumulative distribution function. We assumed that all fires are stand-replacing, typical of this forest type (Murphy *et al.* 2013). Distributions and probabilities were constructed and calculated in *R version 3.5.1* (R Core Team 2018).

We explored three stand age thresholds critical to silvicultural and conservation values: (i) 20 years, or the time period required for maturation of most mountain ash individuals (von Takach Dukai *et al.* 2018); (ii) 80 years, or the minimum time period required to grow merchantable sawlogs (Flint and Fagg 2007); and (iii) 180 years, required to develop adequate hollows suitable for cavity-dependent wildlife in mountain ash forest (Lindenmayer *et al.* 2017).

Recent past and future fire occurrence scenarios

In our study, the recent past, where h equals 0.01 (informed by an average interfire interval of ~107 years outlined above), reflects fire occurrence corresponding with the period of western land management influences including extensive timber harvesting over the past 150 years. A future scenario, where h equals 0.02 and k, r and m are held constant at 0.12, 0.33 and 0.0035 respectively, reflects a projected doubling of fire occurrence by 2070 to an average of one fire per 50 years. There is generally an expectation for increasing fire frequency in Australian temperate forests with global warming (Bradstock 2010; King *et al.* 2013). Further, landscape-scale simulation of a mountainous south-eastern Australian region suggests that fire interval could halve by 2070. This assumes an increase in average daily maximum temperature of 2°C with a commensurate change in other weather variables (Cary 2002), being the midpoint of a full range of projected temperature increases accounting for differences among General Circulation Models (GCMs), a range of climate sensitivities, and a range of plausible future emission scenarios (CSIRO 1996). Similarly, fire-cycle length in south-eastern Australian forests could decrease by 42 to 46% by 2070, depending on success of initial suppression of fires, assuming 50th percentile climate projections across a range of GCMs simulating the high cumulative emission A1FI scenario (King *et al.* 2011). Some landscapes may already be entering disturbance regimes represented by the future fire scenario given recent observations that almost a quarter of all wet and damp forests, an ecological vegetation class including mountain ash forests, on public land in Victoria have burned two or more times in the last 25 years, with some of these areas burning up to four times during that time period (Lindenmayer and Taylor 2020). Further, alpine ash forest, which is functionally similar to mountain ash, has recently been observed burning 2–3 times in 7 years (Bowman *et al.* 2014).

Results

Two key results emerge from comparing fire interval functions, representing diverse underpinning mechanisms determining flammability, in mountain ash forest parameterised for the recent past and the future (Fig. 1).

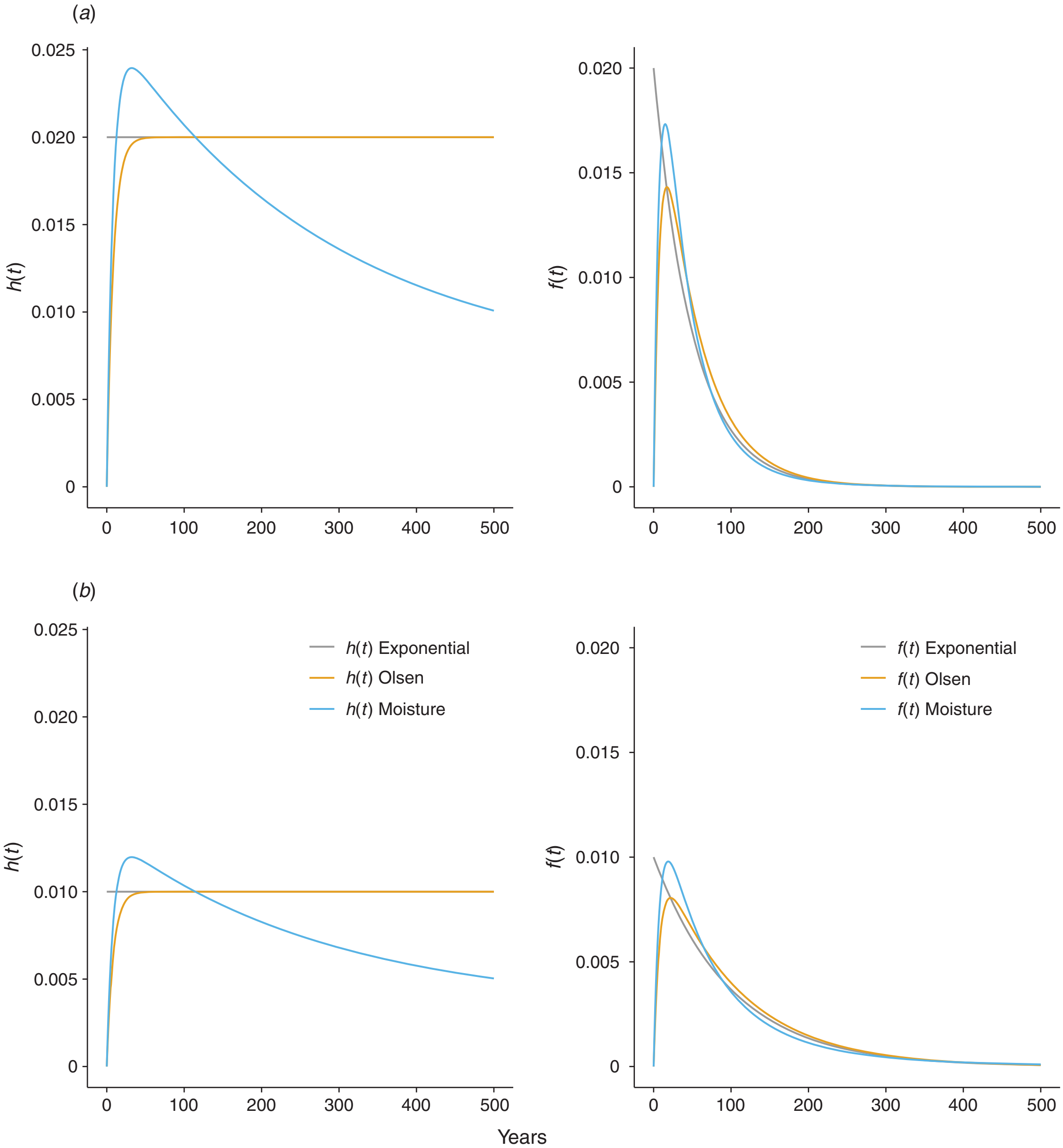

Fig. 1. Theoretical fire hazard functions, $h(t)$, (left panels); and derived fire interval functions, $f(t)$, (right panels) for mountain ash (*Eucalyptus regnans*) forest in the Victorian Central Highlands, Australia, according to three different models of fire hazard (Exponential, Olson and Moisture), each with two values of h (annual probability of fire). Values for h include: (*a*) doubling fire occurrence from recent past, reflecting likely climate change effects, $h = 0.02$; and (*b*) the recent past, $h = 0.01$ (see McCarthy *et al.* 1999).

First, the likelihood of realising key production and conservation thresholds in stand age diminishes markedly for the future fire regime ($h = 0.02$), particularly for sawlog production and creation of adequate hollow-bearing trees. The probability of realising an 80-year or longer fire interval, required for viable sawlog production, declined from ~0.45 for the recent past to ~0.21 for 2070 on average across different hazard functions (Fig. 2, Table 1). Consequently, we predicted only one in five future fire intervals will be sufficiently long to grow sawlogs. Similarly, the probability of realising a fire interval of at least 180 years required for developing adequate habitat hollows declined from ~0.17 for the recent past to ~0.03 in 2070 (Fig. 2, Table 1). Mountain ash population viability, defined here as the probability of realising fire intervals of at least 20 years was highest overall, at ~0.85 and ~0.73 for the recent past and future, respectively (Fig. 2, Table 1).

Second, results for the probability of realising particular thresholds were similar, irrespective of which of the highly mechanistically diverse functions of fire hazard were adopted (Fig. 2, Table 1). This was particularly the case for the longer stand age thresholds, including probability of realising sawlog production, which ranged from 0.43 to 0.49, and probability of hollow occurrence, which ranged from 0.16 to 0.18, for recent

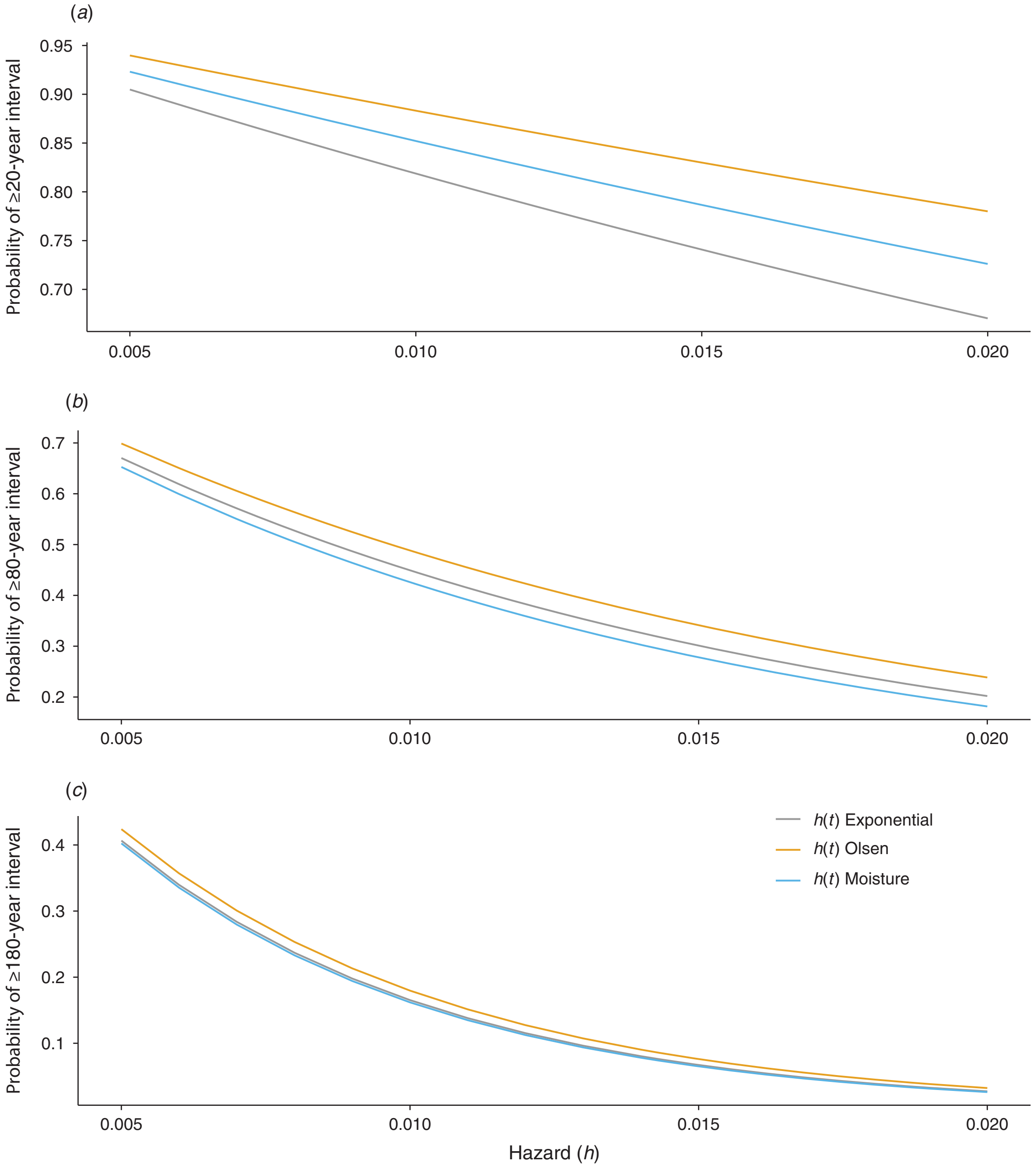

Fig. 2. Probability of a fire interval as long as or longer than specified age thresholds, $1 - F(t)$ for threshold values (*a*) $t = 20$ years; (*b*) $t = 80$ years; and (*c*) $t = 180$ years for mountain ash (*Eucalyptus regnans*) forest in the Victorian Central Highlands, Australia, according to three different models of fire hazard (Exponential, Olson and Moisture). Values for h (annual probability of fire) range from: doubling fire occurrence from the recent past, reflecting likely climate change effects, $h = 0.02$; to halving fire occurrence from the recent past, $h = 0.005$. For the recent past, $h = 0.01$.

fire history ($h = 0.01$) (Table 1). Commensurate ranges of probabilities of realising these thresholds for the future fire regime were 0.18 to 0.24 for sawlog production and 0.026 to 0.032 for hollow formation (Table 1).

Discussion

With climate change, wildfires in temperate forests are likely to become more frequent and widespread (Cary 2002; Westerling *et al.* 2006). This may reduce the probability of mountain ash stands growing to a rotation age for sawlog harvesting (80 years) by more than 50%, and reduce the probability of stands developing adequate hollows (~180 years) by ~80%, as could be inferred from McCarthy *et al.* (1999) assuming the exponential function. These findings remained consistent irrespective of the type of fire interval distribution adopted, indicating robustness to different interpretations of underpinning mechanisms influencing fire occurrence in these forests (Taylor *et al.* 2014).

Table 1. Probability of a fire interval as long as or longer than critical stand ages for species maturation, viable sawlog rotation and development of adequate habitat hollows, for mountain ash (*Eucalyptus regnans*) forest in the Victorian Central Highlands according to three different models of fire hazard (Exponential, Olson and Moisture), each with two values of *h* (average annual probability of fire)

Values for *h* are: recent past, $h = 0.01$; and doubling recent fire occurrence reflecting likely climate change effects, $h = 0.02$

Age (years)	Management relevance	'Hazard' function: Exponential		Olson		Moisture	
	$h =$	0.01	0.02	0.01	0.02	0.01	0.02
20	Maturity	0.819	0.670	0.883	0.780	0.852	0.726
80	Sawlog rotation	0.449	0.202	0.488	0.239	0.426	0.181
180	Adequate hollows	0.165	0.027	0.18	0.032	0.162	0.026

Natural disturbance and the production of hollow-bearing trees

We predict that an increase in fire frequency to an average of one fire every 50 years in mountain ash forests will be unlikely to extinguish the species locally through restricting maturation, similar to McCarthy *et al*. (1999). Nevertheless, current debate on tall, wet eucalypt forests focuses on concerns that the flammability of regenerating stands, coupled with more frequent extreme fire weather, will result in the loss of much of the remaining mature forest (Bowman *et al.* 2014).

Our findings suggest there is a low probability of growing trees to 180 years old, now and in the future, assuming only fire disturbance and noting that probability of reaching this age threshold will be further reduced by forest harvesting. Large old trees of this age are critically important keystone structures in mountain ash ecosystems because of the nesting and denning sites that they provide for many cavity-dependent species (Lindenmayer *et al.* 2017). Populations of these old trees are currently in rapid decline and have almost halved in the past 20 years, with almost no recruitment into this age class (Lindenmayer and Sato 2018). These declines have resulted from extensive wildfires, logging and climate change (Lindenmayer *et al.* 2012, 2016). The effects of more frequent wildfires further precluding the long-term development of old growth stands mean that large parts of mountain ash forest could become devoid of these key attributes of stand structure. This, in turn, has major implications for the medium- to long-term persistence of populations of cavity-dependent fauna, many of which are currently exhibiting rapid rates of decline (Lindenmayer and Sato 2018).

Even under fire regimes of the recent past, our estimate of a probability of only 0.17 of growing forests stands to 180 years old (see also McCarthy *et al*. 1999) is consistent with mountain ash landscapes being already dominated by relatively young forest. An estimated ~98% of mountain ash in the Central Highlands is currently 120 years or younger. Attempts to increase the amount of old-growth forest in the landscape will require large areas of existing 80-year-old forest (dating from extensive 1939 wildfires) to be excluded from timber harvesting.

Fire frequency and sawlog production

Earlier work indicated the optimal age for producing sawlogs in ash-type forests is 100–120 years, longer than the minimum time of 80 years we modelled. Rotation times of 50 years or shorter increase the ratio of pulpwood versus sawlog that is produced (Flint and Fagg 2007). This suggests a need to rethink where sawlogs can be sourced sustainably. One option is to target fast-growing plantations with rotations of 20–30 years. In the state of Victoria, Australia, ~88% of all sawn timber is already sourced from plantations (ABARES 2018) and shorter fire cycles suggest that plantations will become even more important. Further, eucalypt plantations in southern Australia appear less prone to burning than dry native eucalypt forest and are approximately as likely to burn with medium, or greater, severity wet eucalypt native forest (Ndalila *et al.* 2018). Similarly, while *Pinus radiata* plantations are highly flammable (Ndalila *et al.* 2018), they may experience much longer intervals between fire than native forests in the future, even accounting for shortening of intervals across all forest types (King *et al.* 2011).

Irrespective of the origin of sawlogs, our analyses highlight the critical need for the impacts of natural disturbances to be factored into forest planning, especially when calculating the probability of forest stands being available for longer-rotation sawlog production (Van Wagner 1978; Burgman *et al.* 1994; Armstrong 2004; González *et al.* 2005; Gauthier *et al.* 2015). Failure to account for future disturbances such as wildfires, which has been the case in Victorian native forest management up until now (Lindenmayer 2017; VEAC 2017), increases the risk of overharvesting forests to meet timber yields.

Limitations and caveats

We made simplifying assumptions in determining our findings. First, we were unable to account for uncertainty in our estimates of probability of achieving fire interval thresholds given uncertainty estimates are unavailable for most parameters of the flammability functions. Instead, we quantified differences in probability based on mean fire interval for the recent past and a future projection.

Second, we did not model the relationships indicating that fires are likely to be lower-severity when occurring in older forests (Taylor *et al.* 2014), while extensive areas of young, early successional forest are increasingly susceptible to burning at high severity (see also Thompson *et al.* 2007; Lindenmayer *et al.* 2011). This means we have likely overestimated the probability of forests reaching the stand age thresholds we specified. Moreover, if stand-replacing wildfires eventually become extremely frequent, there is a strong risk that some mountain ash forests will be eliminated altogether and replaced by other kinds of vegetation such as acacia-dominated open woodland (Burns *et al.* 2015). Similar outcomes have been forecast to occur in fire-prone systems elsewhere in the world (e.g. western USA; Odion *et al.* 2010; Miller *et al.* 2019).

Third, parameterisation of the models we have invoked assumes a level of equilibrium between the forests we model and their fire regimes, both for the recent past and the future. Equilibrium conditions do not occur in all fire-prone ecosystems (Cumming *et al.* 1996; McCarthy *et al.* 2001) and this warrants some caution in interpreting results. However, presumably the effect of any deviation from this assumption, with respect to our empirical- and simulation-derived estimates of long-term probability of fire (h) would be relatively less important compared with the effect of doubling h, or effectively halving fire interval, for 2070 as a result of climate change.

Finally, while we adjusted the annual probability of fire, h, among our fire scenarios, other model parameters including those governing fuel dynamics in the Olson function, and additional rates governing flammability dynamics in the moisture function were not adjusted for the future scenario. Projecting changes in bushfire fuel amount, decomposition and condition is among the most challenging aspects of forecasting future fire regimes (Cary *et al.* 2012). Nevertheless, the consensus for our findings across different hazard functions for mountain ash forests gives us confidence in the robustness of our results.

Conflict of interests

The authors declare no conflicts of interests.

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