Managing interacting disturbances: lessons from a case study in Australian forests

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Abstract

1. Ecosystems are shaped by a range of drivers including human and natural disturbances. They also may be subject to interactions between disturbances which can affect ecological processes, biodiversity, and ecosystem condition; yet few ecosystems have been subject to multiple studies of the effects of interacting disturbances. This limits understanding of ways to mitigate the impacts of interacting disturbances.

2. Over the past 37 years, we have completed a range of studies of interacting effects in the Mountain Ash (*Eucalyptus regnans*) forests of south-eastern Australia. Here we summarize evidence for interacting disturbances in this ecosystem. This includes evidence of linked or coupled disturbances (termed interaction chains; (*sensu* Foster et al., 2016)) between logging and subsequent fire severity. We also describe effects of other interacting disturbances such as those resulting from post-fire (salvage) logging as well as landscape-level, spatio-temporal changes in forest cover associated with logging and wildfires.

Synthesis and applications. Insights from research in Mountain Ash forests provide broader lessons for managing interacting disturbances in forest ecosystems. These include the importance of cataloguing and mapping multiple disturbances in both space and time and developing conceptual models of ecosystem dynamics and ecological processes. Where there is a high risk of interactions between disturbances, appropriate management actions could include: **(1)** eliminating some drivers or re-assessing levels of human extraction of resources, **(2)** reducing the spatial and/or temporal overlap of drivers, and **(3)** identifying leverage points where management actions are most likely to be effective.

KEYWORDS: Wildfire, clearcutting, salvage logging, interaction chains, linked disturbances, Mountain Ash forests

1. Introduction

The Earth's terrestrial environments are increasingly subject to natural and human disturbances (Seidl et al., 2014; Sommerfeld et al., 2018). Some of these disturbances can interact (Buma 2015; Côté, Darling & Brown 2016; Wang et al., 2019), and this may further compound the effects of each perturbation (Lindenmayer, Thorn & Banks 2017; Vollstadr et al., 2017; Barlow et al., 2018). Indeed, interacting disturbances have been shown to have profound effects on ecosystem structure, function and biodiversity (Burton & Boulanger 2018). Despite the increasing literature on interacting disturbances, however, few studies have empirically quantified how they affect a range of taxa and multiple processes in the same ecosystem (Côté, Darling & Brown 2016). Therefore, for many ecosystems worldwide, it remains unclear how biodiversity and ecosystem processes might respond to interactions between disturbances, how disturbances themselves might interact, or how the impacts of disturbance might be mediated or exacerbated by other factors (e.g. climate). This has left major gaps in our understanding about how to design policies and implement strategies to effectively mitigate ecologically damaging interactive effects (Foster et al., 2016; Leverkus et al., 2018).

Here we summarize evidence for the effects of interacting disturbances on ecological processes, biodiversity, and ecosystem condition in the Mountain Ash (*Eucalyptus regnans*) forests of the Central Highlands of Victoria, south-eastern Australia. We use our case study to provide lessons on, and policy responses to, interacting disturbances in managed forest environments. We highlight the importance of different kinds of studies for developing an improved understanding of interacting disturbance effects and, in turn, creating both conceptual models of ecosystem dynamics and robust assessments of ecosystem condition.

These approaches are critical for identifying ways to respond to multiple disturbances in managed forest ecosystems.

2. Mountain Ash forests

Mountain Ash eucalypt forests occur in the 80 x 60 km Central Highlands region of Victoria, Australia (Figure 1). They are dominated by Mountain Ash trees of a single age cohort that regenerated following previous disturbance. If left long enough (150-550 years old), old growth stands of Mountain Ash trees can reach heights of 100 m. Mountain Ash forests generate almost all of the water for Melbourne, store large amounts of carbon, and support significant biodiversity (Keith et al., 2017), including species of conservation concern (e.g. Leadbeater's Possum (*Gymnobelideus leadbeateri*) and Greater Glider (*Petauroides volans*)) (Lindenmayer & Sato 2018).

The primary form of natural disturbance in Mountain Ash forests is wildfire, with fires typically being high-severity, stand-replacing events with an average return interval of ~ 75-150 years (McCarthy, Gill & Lindenmayer 1999). However, in the past century there has been five major and at least four smaller wildfires in the region. Mountain Ash trees generally produce only limited amounts of viable seed until they are 25-30 years old (von Takach Dukai, Lindenmayer & Banks 2018). Most seed is stored in the canopy (rather than soil), with seeds released from the canopy during wildfire, triggering germination (Smith et al., 2016). Thus, whilst fire is essential for the regeneration of Mountain Ash forests, if fire is too frequent or burns young stands, regeneration can be compromised and Mountain Ash forest replaced by *Acacia* spp. woodland (Ashton 1981). No species of native mammals and only one species of bird are early successional specialists in Mountain Ash forests. This is possibly because Mountain Ash forests grow quickly following disturbance and the period before canopy closure in regenerating stands is only ~3-5 years (Lindenmayer et al., 2019c).

Clearcut logging is the primary form of human disturbance in Mountain Ash forests. It involves the removal of all merchantable trees from a cutblock. Logging debris is left on the forest floor for ~ 1-2 years before being burned in a high-intensity fire then restocked with eucalypt seeds to re-establish a new stand of overstorey Mountain Ash trees. Widespread clearcutting commenced in Mountain Ash forests in the mid-1970s and the nominal rotation time between harvesting at a site is 80 years (Flint & Fagg 2007).

A third kind of disturbance in Mountain Ash forests is salvage logging in which fire-damaged stands are harvested to recover some of the economic value of the wood. The types of disturbances in salvage logging are similar to those in clearcutting, except the sequence of "sub-disturbances" is reversed. That is, logging occurs after fire whereas in conventional logging, green forests are logged prior to being burnt to stimulate stand regeneration. Salvage logged stands are often burned a second time before being artificially reseeded to instigate regeneration of new stands of Mountain Ash trees.

3. Examples of interactions among disturbances in Mountain Ash forests

Over the past 37 years we have conducted an array of true experiments, quasi-experiments, long-term observational studies and opportunistic studies (*sensu* Cunningham & Lindenmayer 2016) in Mountain Ash forests. Some of these investigations contain evidence of interactive effects of disturbances for a variety of taxa and ecosystem properties, particularly when disturbances occur in rapid succession such as logging operations which affect the severity of subsequent fire, logging directly after fire, and recurrent wildfire (Appendix S1). For example, there is evidence of coupled or linked disturbances (Buma

2015) (also termed an interaction chain) between logging and wildfire in which fire severity is significantly influenced by the age of the forest prior to a fire. The effect is a non-linear interaction in which young stands < 7 years old regenerating after logging generally do not burn, but after this the risk of crown fire increases strongly and does not decline until forests exceed ~ 40 years old (Taylor, McCarthy & Lindenmayer 2014). Similar kinds of interactions between stand age and forest flammability have been found in other parts of the world (e.g. Zald & Dunn 2017; Tiribelli et al., 2018; Zylstra 2018; Winoto-Lewin et al., 2020). Several factors likely contribute to these stand age-flammability relationships. These include: **(1)** Increased fuel loads resulting from the large amounts of logging debris left after harvesting, some of which is not consumed by fires deliberately lit to regenerate cutblocks. **(2)** The highly significant reduction in mesic shrub-layer plants such as tree ferns following logging operations. And, **(3)** The high density of young regrowth trees in regenerated forests which self-thin and self-prune, creating large amounts of fine and medium fuels (Taylor, McCarthy & Lindenmayer 2014).

In another example of interacting disturbance effects, post-fire (salvage) logging always follows a prior disturbance (i.e. wildfire) and has greater impacts on soils and vascular plants in Mountain Ash forests than either single disturbance in isolation (Blair et al., 2016; Bowd et al., 2019; Appendix S1). Repeated wildfires at short return intervals can depress levels of stands regeneration (Smith et al., 2014), reduce soil nutrients (Bowd et al., 2019), and elevate rates of loss of key elements of stand structure like large old hollow-bearing trees that are keystone nesting and denning structures for ~ 40 species of cavity-dependent fauna (Lindenmayer et al., 2019c). Repeated fires also can impair the recruitment of large old hollow-bearing trees because they are killed and rapidly collapse before they begin to develop cavities.

Other studies have reported strong effects of individual disturbances. For example, numbers of hollow-bearing trees in unharvested forest patches decline more rapidly on burnt than unburnt sites, and are also negatively related to the amount of logging in the landscape surrounding a patch (Appendix S2). Importantly, the combination of repeated fires, widespread logging, high fire-proneness of young logged and regenerated stands, and post-fire salvage logging, can increase the frequency and severity of disturbances across entire landscapes . This can largely eliminate old growth stands and prevent young stands from reaching ecological maturity (Lindenmayer et al., 2011) and potentially even trigger a regime shifts in which the Mountain Ash ecosystem is at high risk of collapse and being replaced by a different ecosystem (Burns et al., 2015) (Appendix 3).

4. Lessons for managing multiple interacting disturbances

Many forest ecosystems are subject to interacting disturbances that may affect ecological condition, biodiversity, and ecosystem processes (e.g. Cochrane & Barber 2009; Zald & Dunn 2017; Barlow et al., 2018; Rhoades et al. 2018). Mountain Ash forests are an example of such an ecosystem and work in them to date provides lessons for managing other highly disturbed forest ecosystems worldwide (Watson et al., 2018).

First, important insights can be gained from conducting different types of studies in the same ecosystem (Appendix S1) to gain a more complete picture of how disturbances interact. Consistent outcomes from different studies also may reinforce the evidence-base for the impacts of interactions between disturbances. This was the case for the detrimental impacts of salvage logging in Mountain Ash forests identified from both opportunistic post-disturbance studies and quasi-experiments (Blair et al., 2016; Bowd et al., 2019; Appendix S2). Insights from different studies can also facilitate spatial and temporal mapping of disturbances, and help in assessing the implications of overlapping disturbances for ecosystem condition, as well as resource availability for extractive industries. As an example, Burton and Boulanger (2018) mapped and projected the spatial occurrence of regional combinations of disturbances from fire and insect attacks in the forests of British Columbia. A key part of such efforts must be to map both recent and past disturbances. This can assist with comparisons of current and historic disturbance regimes, and whether the sequence of human and natural disturbances is outside natural bounds for disturbance regimes in a given ecosystem. This is important because repeated disturbances in rapid succession can affect the numbers and types of biological legacies (e.g. resprouting plants, seed stocks and large old trees) persisting after disturbance, which may, in turn, have a marked influence on stand regeneration and animal biota (Lindenmayer et al., 2019c). Rapid return of high-severity and interacting disturbances also may make an ecosystem vulnerable to collapse (Valiente-Banuet & Verdu 2013). Indeed, in the case of Mountain Ash forests, mapping of past and recent disturbances, coupled with the risks of future disturbance underpinned a formal assessment under IUCN Red Listed Ecosystem criteria. This revealed the ecosystem is Critically Endangered due to the risks of ecosystem collapse as a result of multiple disturbances (Burns et al., 2015; Appendix S3).

A second lesson emerging from completing different studies of interacting disturbances in the same ecosystem is that it can facilitate the development of more holistic conceptual models of ecosystem dynamics. This can help guide enhanced policies for improved management. For example, we developed a new conceptual model of Mountain Ash forests which illustrates how an ecosystem state that includes limited amounts of old growth forest in the landscape (where fire severity is lower (Taylor, McCarthy & Lindenmayer 2014)) place the ecosystem at risk of additional fire and salvage logging (Appendix S3). This, in turn, reinforces the ecosystem-wide dominance of young fire-prone forest, elevates the risk of widespread regeneration failure, increases rates of loss of keystone structures and rates of loss of associated biodiversity (Appendix S3).

As we describe further below, we suggest that where empirical data, conceptual models, mapping and formal assessments indicate the risk of interactions between disturbances is high, and likely to have significant adverse consequences, management could work towards: **(1)** eliminating some drivers or re-assessing levels of human extraction of resources, **(2)** reducing the spatial and/or temporal overlap of drivers, particularly in critical parts of the landscape such as refugia, and **(3)** identifying leverage points where management actions are most likely to be effective (Figure 2).

4.1 Reduce the number of drivers in an ecosystem

Reducing the total amount of disturbance in an ecosystem and reducing the number of drivers of disturbance are important ways to manage effects of interacting disturbances. In Mountain Ash forests, reducing the numbers of drivers of disturbance would entail limiting the amount of logging. This recommendation will apply to many other native forests globally where levels of intact forest are currently limited (Watson et al., 2018). Where it is not possible to entirely remove human disturbances such as logging, resource availability and rates of extraction (such as for sustained yields of timber volumes) need to be carefully assessed relative to recent past, current and likely future levels of natural disturbance. Failure to do so risks extracting resources at unsustainable levels, potentially leading to the collapse of dependent industries (e.g. timber and water production) and large losses of biodiversity. Where natural disturbance frequencies are likely to increase in the future (e.g. fire under global climate change), there may be a need to review whether resource extraction industries can remain viable in the face of these interacting disturbances.

4.2 Reduce the likelihood of disturbances co-occurring in space and time

Some ecosystem drivers, such as fire, can neither be eliminated nor easily controlled over large spatial scales, making it important to limit the overlap between unmanageable and manageable disturbances (e.g. logging) in biologically important locations such as refugia, or areas supporting keystone structures. Intact old growth stands are refugia in many forest types (Watson et al, 2018) including in Mountain Ash forests where they are critical for birds (Lindenmayer et al., 2019b). Large old trees are keystone structures that should be protected from the impacts of interacting disturbances in many forest ecosystems (Lindenmayer and Laurance 2017), including Mountain Ash forests. Protecting refugia and keystone structures may require establishing buffers, particularly where their integrity can be undermined by edge effects arising from disturbances in the adjacent landscape (Appendix S3). For example, in Mountain Ash forests, buffers of unlogged forest up to 200 m have been recommended to protect large old trees from increased windthrow arising from clearcutting in the surrounding landscape (Lindenmayer et al., 2019a).

A key approach to managing multiple drivers is to limit the potential for disturbances to interact over short periods of time. Salvage logging is an example of avoidable disturbances in rapid succession. What constitutes “rapid succession” is context-specific and dependent on the natural disturbance interval. For example, in Mountain Ash forests, there can be interactions between logging and fire up to 40 years apart (Taylor, McCarthy & Lindenmayer 2014).

4.3 Identify leverage points for effective management

Leverage points are those where management interventions may have a large positive effect (Abson et al., 2017). Management of some drivers (e.g. climate change or fire) may be more difficult to tackle, than others (e.g. logging). It can be valuable to identify leverage points that focus on disturbances that can be moderated, to either reduce the likelihood of a second linked disturbance, or reduce the impact of other co-occurring disturbances that are more difficult to manage. For example, while wildfire in Mountain Ash forests is difficult to control directly due to linked interactions, fire severity is lowest in old growth forest (Taylor, McCarthy & Lindenmayer 2014). Managers could therefore plan to significantly expand the geographic extent of old growth to reduce fire risk at a landscape scale.

Other aspects of effective management include planning actions well in advance of interacting disturbances. For example, high frequency, high-severity disturbance of widespread young Mountain Ash forest carries a risk of extensive regeneration failure of overstorey trees. A risk mitigation approach under such circumstances may be to collect and store large quantities of Mountain Ash seed well in advance of major disturbances. This can help ensure that Mountain Ash can be re-established following repeated wildfires. In other forest ecosystems (where seed storage is not possible), there may a need to determine if there are "triage landscapes" that are too degraded for cost-effective and ecologically-effective restoration to occur (*sensu* Hobbs, Cramer & Kristjanson 2003). Careful consideration may be needed for what actions are appropriate in such triage landscapes. However, there can be considerable value in maintaining keystone structures (such as large old trees) in heavily degraded landscapes as they act as micro-refuges for some elements of biodiversity in new ecosystems (Fitzsimons & Michael 2017).

5. Concluding comments

Few investigations have tested for the effects of interacting disturbances on multiple taxa and processes in the same ecosystem. An array of studies in Australian Mountain Ash forests have highlighted the spatial and temporal complexity of interacting disturbance effects and provide general lessons for forest management. Where there is a high risk of interactions between disturbances that produce adverse impacts, management actions could eliminate some drivers, reduce the spatial and/or temporal overlap of disturbances, and identify key leverage points where management actions might be particularly effective.

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Author contributions

All authors conceived the ideas for this paper, contributed to manuscript writing and gave approval for publication.

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Data accessibility

Data have not been archived because this article does not use data.

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Figures

Figure 1. Location of study sites (black squares) in the Central Highlands of Victoria, south-eastern Australia.

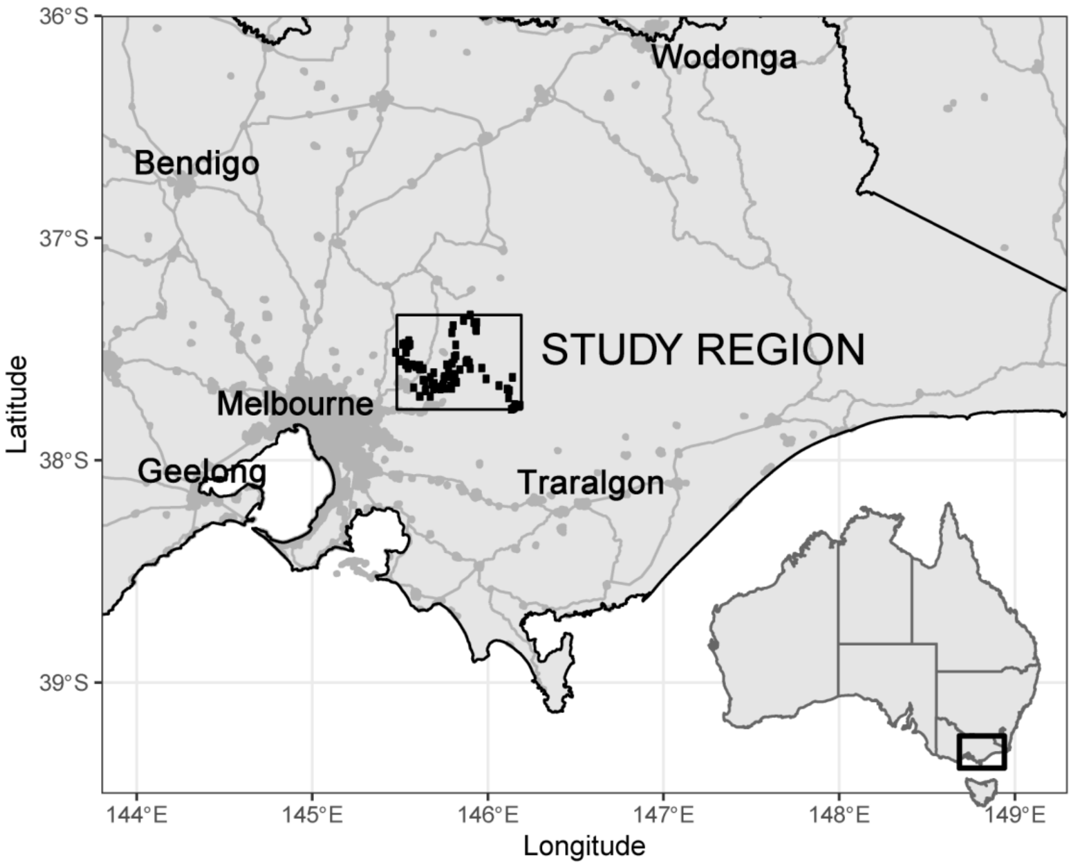
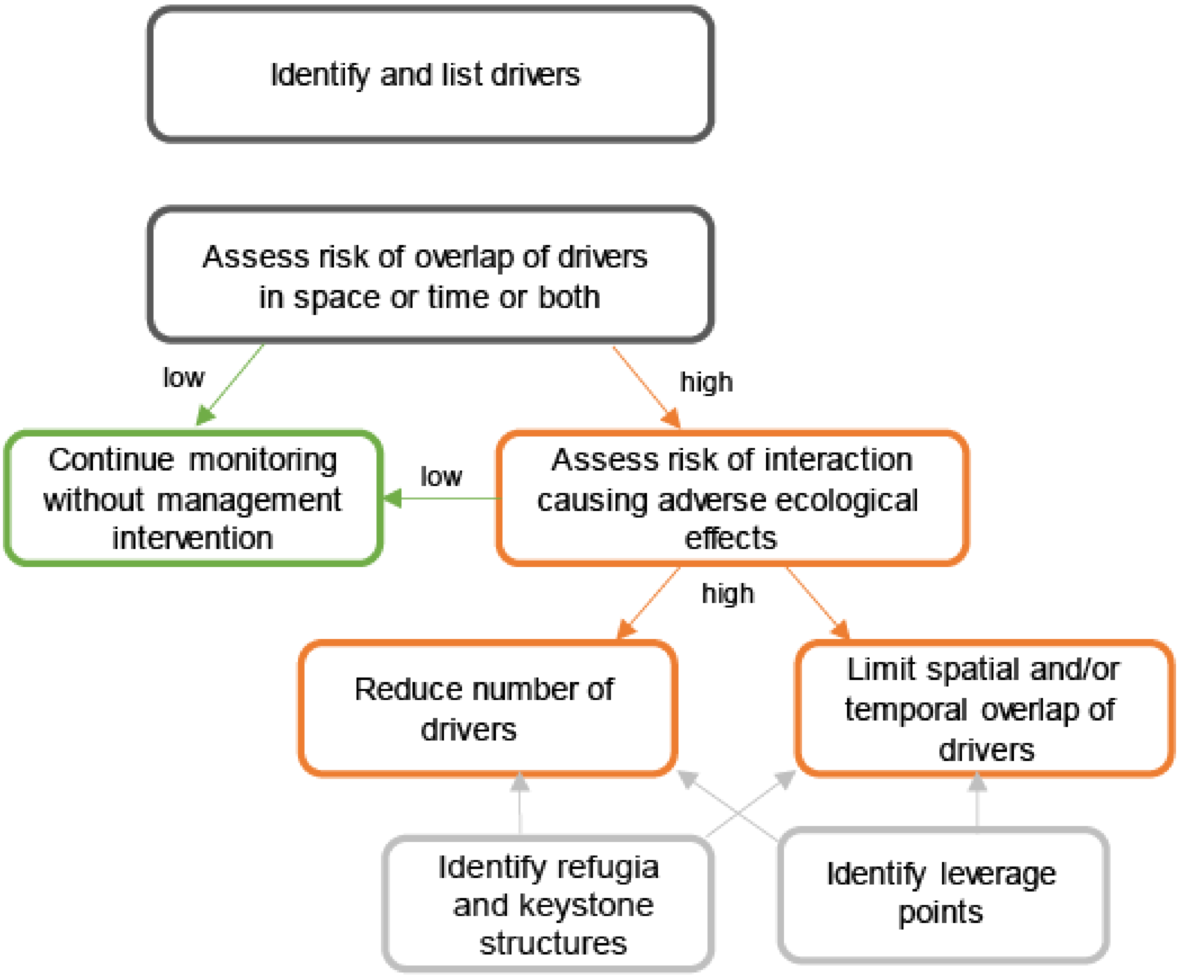


Figure 2. Steps for assessing and managing interacting disturbances and the number of drivers of disturbance.



Supporting Information

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Appendix S1: Examples of different types of studies conducted on fire and logging and (in a small number of cases) climate and their interaction in the Mountain Ash forests. Definitions of interaction chains and interaction modifications are from (Foster et al., 2016). Examples are listed by study type.

Broad type of investigation*	**Examples of interactions between drivers**	**Description of effects**	**Citation/s**
Quasi-experiment	Post-fire salvage logging affects plant and animal biota	Fire in mature forest triggers post-fire salvage logging which is an example of an interaction chain. Salvage logging has significant negative effects on soils, vascular plants, tree ferns, and forest birds that are more severe than fire or logging alone which is an example of an interaction modification	(Blair et al., 2016; Lindenmayer et al., 2018b)

Opportunistic study	Fire severity is altered by previous logging operations	Logged and regenerated areas are significantly more likely to burn at higher severity demonstrating a non-linear interaction chain	(Taylor, McCarthy & Lindenmayer 2014)
Opportunistic study	Past fire and logging alters regeneration dynamics	Fire in young regenerating forest is more likely to cause recruitment failure of plants demonstrating an interaction modification	(Ashton 1981; Smith et al., 2014)
Opportunistic study	Fire and logging have cumulative spatial effects	Elevated fire severity effects created by logging (see above) accumulate over multiple cutovers across landscapes to increase spatial contagion of fire and prevent mature forest from developing, demonstrating an interaction chain	(Lindenmayer et al., 2011)
Long-term observational study	Past fire or logging alters effects of fire.	Formation of key habitat resources from fire-damaged and fire-killed large old trees is dependent on the age of forest at the time it is burned (i.e. time since fire or time since logging)	(Lindenmayer et al., 2019)
Long-term observational study	Past fire, logging and climate alter post-fire recovery	Seedling germination following fire is impaired in younger forests and on warmer, low elevation sites	(Smith et al., 2016)
Opportunistic study	Repeated fire, logging and post-fire salvage logging alter post-disturbance	Plant communities and levels of key soil nutrients are significantly altered by significantly altered by repeated	(Bowd et al., 2018; Bowd et al., 2019)

	recovery and forest conditions	wildfires, by past clearcutting, and especially post-fire salvage logging	
Long-term observational study	Landscape-level amounts of fire and logging drive a decline in keystone structures	The abundance of large old hollow-bearing trees declines significantly with increasing amounts of harvesting in the surrounding landscape and an interaction with wildfire	Appendix S2
Long-term observational study	Climate and fire influence bird populations	Bird population recovery following fire is impaired on climatically cool sites and in response to wet and cool weather	Lindenmayer et al. unpublished data
Experiment	Post-harvesting regeneration burns affect biodiversity	Clearcutting reduces small mammal occurrence, but declines are most severe when a combination of cutting and post-harvest fire are implemented. There was an interaction between logging stage and harvesting type with impacts on small mammals more muted when variable retention harvesting methods are employed and islands of forest are retained within cutblocks	(Lindenmayer et al., 2010)

*Based on the classification of study types by Cunningham and Lindenmayer (2016).

Appendix S2: Long-term ecological observational study and related analyses of the abundance of large, old hollow-bearing trees

We have completed several studies of the abundance and rate of collapse of large, old hollow-bearing trees over the past 20 years and details associated with that work are described in (Lindenmayer et al., 2012; Lindenmayer et al., 2018a). For the new analyses employed in this study, we used data on the abundance of large, old hollow-bearing trees that were gathered at 161 long-term sites.

A large old hollow-bearing tree was defined as any tree with an obvious cavity (as determined using a pair of 8 x 40 binoculars). All hollow-bearing trees were counted and then mapped on each 1 ha site in 1997. Surveys were repeated in 2005, 2009, 2012, and 2015 and we recorded whether a given tree on a site remained standing and whether any new trees had developed cavities since the preceding survey. We also compiled data on the extent of fire and logging in the landscape surrounding each of our long-term sites. Notably, none of our sites were logged, but the landscape surrounding some of our survey sites has been subject to clearcutting.

The amount of logged forest within wood production areas has increased over time with an increasing number of cutblocks having been harvested for timber and pulpwood (DJPR 2019). The exception is deep within closed water catchments and reserves where logging is excluded. We calculated a spatially-weighted proportion of 25 m x 25 m pixels logged within a 2500 m x 2500 m square surrounding each survey site in the previous 20 years

The 2009 wildfire was the only major fire that occurred during our study. Using spatial data obtained from the Government of Victoria on forest cover following the 2009 fires (DEPI 2014), we calculated a spatially-weighted proportion of 25 m x 25 m pixels burned 2500 m x 2500 m square surrounding each survey site. In addition, we measured whether a site had been burned (or not) in the 2009 wildfires.

The dominant age of the 1ha site was also measured and classified into one of four categories (old growth, 1939, 1960-1990s and mixed age).

Due to the major wildfire occurring partway through our long-term study, we chose to analyze the data as a BACI (Before-After Control-Intervention) design. That is, the effect of fire is measured by the interaction between fire (at the site level) and year. Landscape level fire was highly correlated with site level fire and was removed from the analysis. In addition, stand age was highly correlated with amount of logging in the surrounding landscape, and was also not considered further.

We modelled the number of hollow-bearing trees on site with a multi-level Bayesian Poisson regression with Site as random effect. Specifically, we used the following model:

$$LP_{ij} = Site_i + Fire_i + Year_{ij} + Fire_i X\ Year_{ij} + Harvest_{ij} + Fire_i\ X\ Harvest_{ij} + Year_{ij}\ X\ \ Harvest_{ij} + Fire_i X\ Year_{ij}\ X\ Harvest_{ij}$$

where $Site_i$ is the site random effect, $Fire_i$ is the burn status of the site established in 2009 but fixed for prior years consistent with the BACI design, $Year_{ij}$ is the year effect, $Harvest_{ij}$ is the time varying measure of logging from 1950 to the current year. $Fire_i X\ Year_{ij}$ is the BACI treatment effect and $Fire_i X\ Year_{ij}\ X\ Harvest_{ij}$is the interaction between logging and fire. We looked at all possible models and chose the simplest model within 2 units of the best fitting model as judged by the Widely Applicable Information Criteria (WAIC) (Gelman, Hwang & Vehtari 2014; Vehtari, Gelman & Gabry 2016).

The models were fit with the brms package (Bürkner 2017) in R 3.6.1 (R Core Team 2019).The models were run with 4 chains each, for 5.000 iterations with a warm-up of 1,000 iterations and a thinning factor of 4, resulting in 4,000 samples for posterior inference. We assessed the convergence of the chains with $\hat{R}$ statistic, which was less than 1.01 in all cases, indicating adequate convergence for all model parameters. We report 95% credible intervals for model parameters. Note all continuous variables have been standardized by subtracting their mean and dividing by their standard deviation prior to analysis.

The analyses described above contained strong evidence of a decline in hollow-bearing tree abundance with increasing amounts of harvesting and an interaction between site-level fire and year (Figure S1).

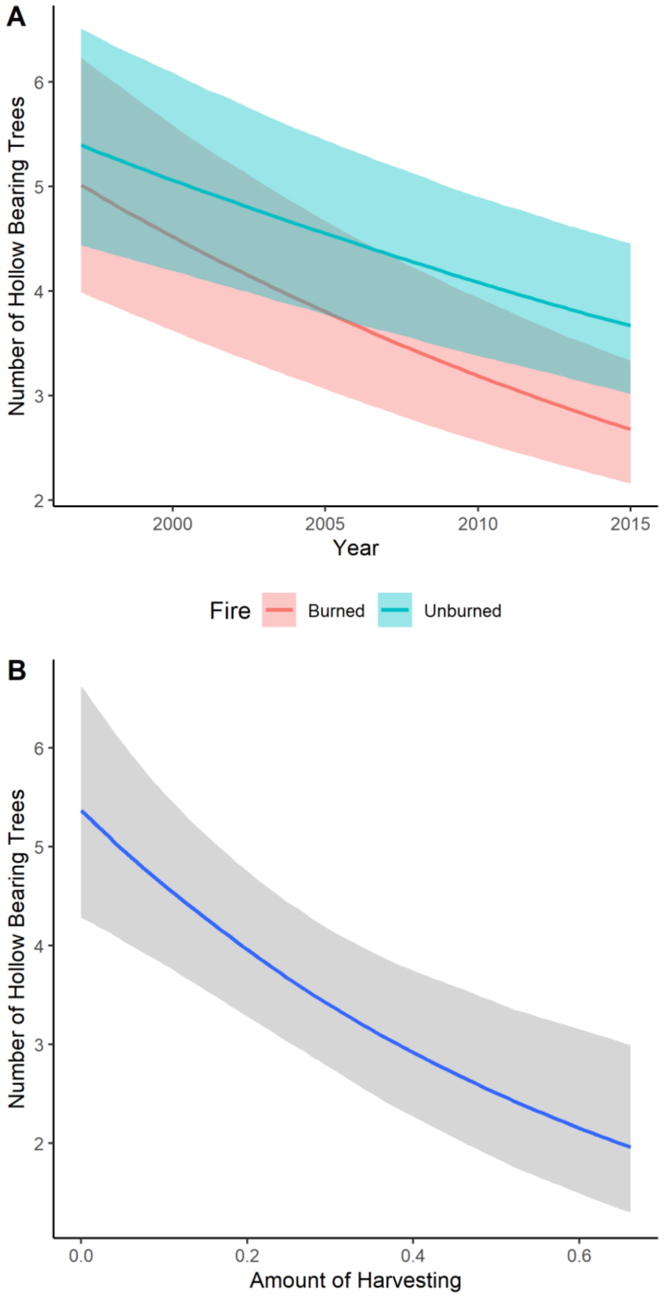
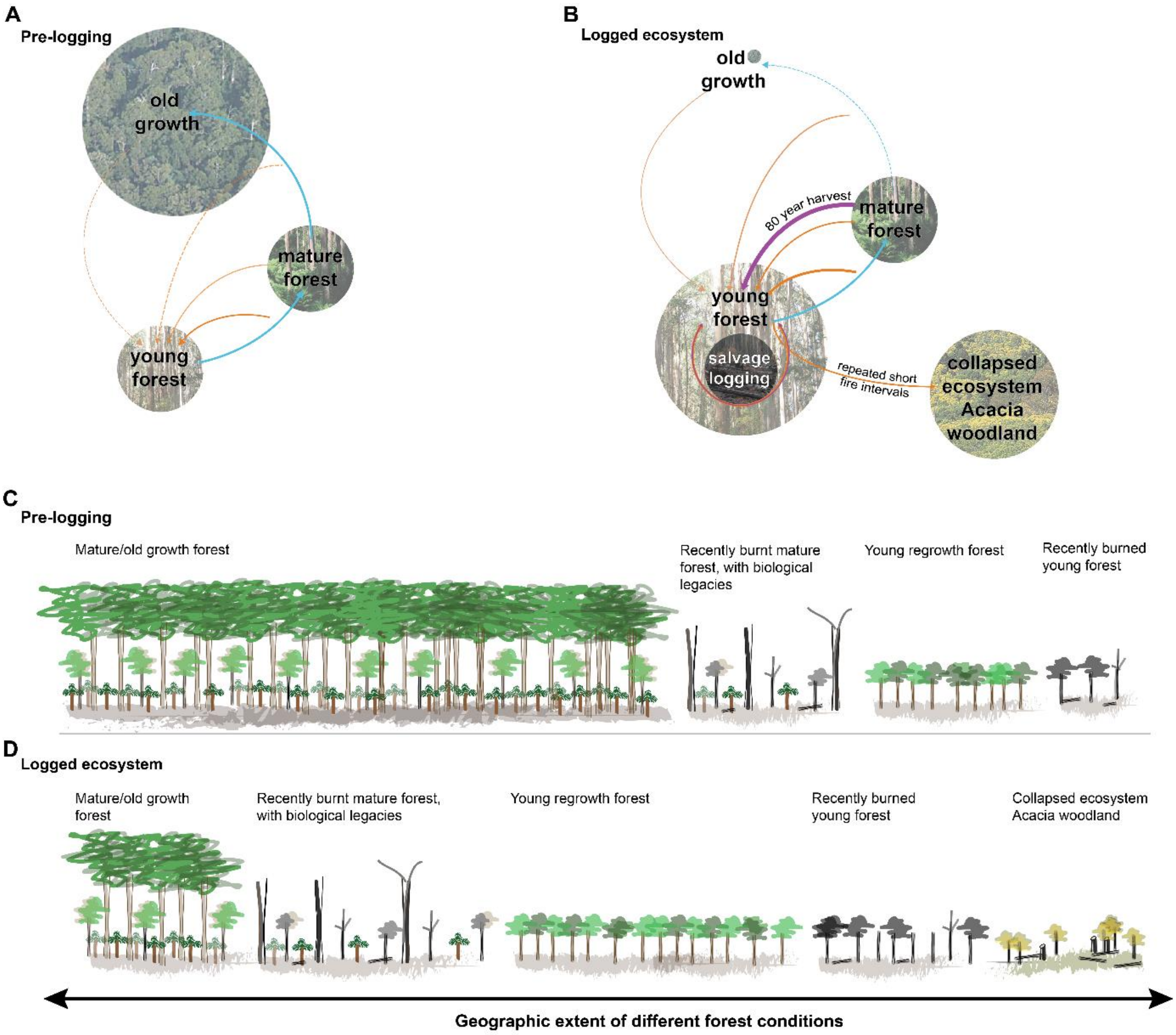


Figure S1. Relationships between the abundance of hollow-bearing trees, the abundance of hollow-bearing trees, the presence of fire at the site level, and the amount of harvesting in the surrounding landscape. A) shows the interaction between fire and survey year on the number of hollow bearing trees at the site level. B) shows the effect of amount of harvesting in the surrounding landscape and hollow bearing tree abundance.

Appendix S3: Conceptual model of the Mountain Ash ecosystem constructed from insights from multiple kinds of studies and showing interactions between natural disturbance (wildfire) and human disturbance (clearcutting).

The proportion of forest in different age classes of Mountain Ash forest (old growth [> 120 years old], mature [~ 80 years old]) and young forest [0-40 years old] as reflected by the size of the circles in the two sub-models and which broadly approximates what occurred in pre-European forest landscapes (model A) where old growth stands comprised up to 60% of the ecosystem (Lindenmayer & McCarthy 2002) and currently (model B) where 1.16% of the ecosystem is old growth (Lindenmayer et al., 2012). Mountain Ash trees dominate all stand ages, except in a collapsed system. Blue lines represent maturation of forest from young stands to mature and eventually old growth stands. Orange lines represent fires that reduce the age of the stands of forest through stand-replacing disturbance. The purple line corresponds to stand-replacing clearcut logging operations that occur on a rotation of 80 years or less. The thickness of lines highlight the prevalence of disturbances or maturation processes, with dashed lines corresponding to processes that are rare. Model B shows the Mountain Ash ecosystem which is subject to repeated fires, logging and the combination of both interacting processes (including salvage logging and a logging-elevated fire severity interaction chain; see text). The greater thickness of orange lines in model B, compared with A, even for mature and old-growth forest, reflects landscape effects, where small patches of old growth forest in these heavily disturbed environments are at significantly greater risk of being burned due to being surrounded by young, fire-prone forest. The ecosystem in model B is characterized by 98.8% of the forest estate that is 80 years or younger (Lindenmayer et al., 2012) and at high risk of repeatedly reburning. It has an added step in which the Mountain Ash ecosystem collapses and is replaced by an *Acacia*-dominated woodland.


A
Pre-logging
old growth
mature forest
young forest
B
Logged ecosystem
old growth
80 year harvest
mature forest
young forest
salvage logging
repeated short fire intervals
collapsed ecosystem Acacia woodland
C
Pre-logging
Mature/old growth forest
Recently burnt mature forest, with biological legacies
Young regrowth forest
Recently burned young forest
D
Logged ecosystem
Mature/old growth forest
Recently burnt mature forest, with biological legacies
Young regrowth forest
Recently burned young forest
Collapsed ecosystem Acacia woodland
Geographic extent of different forest conditions

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