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The interactions among fire, logging, and climate change have sprung a landscape trap in Victoria's montane ash forests

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Abstract Ecosystems are influenced by multiple drivers, which shape ecosystem state and biodiversity. In some ecosystems, interactions and feedbacks among drivers can produce traps that confine an ecosystem to a particular state or condition and influence processes like succession. A range of traps has been recognized, with one of these – "a landscape trap" first proposed a decade ago for the tall, wet Mountain Ash and Alpine Ash forests of Victoria, south-eastern Australia. Under such a trap, young flammable forest is at high risk of reburning at high severity, thereby precluding stand maturation, and potentially leading to ecosystem collapse. These young forests are more common because recurrent wildfire and widespread clearcutting have transformed historical patterns of forest cover from widespread old-growth with small patches of regrowth embedded within it, to the reverse. Indeed, approximately 99% of the montane ash ecosystem is now relatively young forest. Based on new empirical insights, we argue that at least three key inter-related pre-conditions underpin the development of a landscape trap in montane ash forests. A landscape trap has been sprung in these forests because the pre-conditions for its development have been met. We show how inter-relationships among these pre-conditions, leading to frequent high-severity fire, interacts with life history attributes (e.g., time to viable seed production) to make montane ash forests (e.g., which have been highly disturbed through logging and frequent fire) vulnerable to ecosystem collapse. We conclude with the ecological and resource management implications of this landscape trap and discuss how the problems created might be rectified.

Keywords Disturbance · Logging · Fire · Landscape traps · Eucalypt forest · Australia

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Introduction

Ecosystems are shaped by many drivers, including human and natural disturbances. They are also subject to interactions among disturbances, which can profoundly affect ecosystem condition, ecological processes and biodiversity (Buma 2015; Burton et al. 2020; Cote et al. 2016; Lindenmayer et al. 2020; Simard et al. 2011). Some disturbance interactions involve feedbacks (Burton et al. 2020; Cochrane and Laurance 2008), leading to regime shifts into alternative stable states (Acacio et al. 2009; Folke et al. 2004; Paritsis et al. 2015) or ecosystem collapse (Valiente-Banuet and Verdú 2013). These include *linked* disturbance interactions, whereby multiple disturbances interact to influence the extent, severity, or probability of occurrence of another disturbance (Simard et al. 2011). Examples of such interactions include a negative interaction between bark-beetle outbreaks and the probability of an active crown-fire in North American lodgepole pine forests (Simard et al. 2011), and a positive interaction between anthropogenic climate change and the likelihood of recent wildfires in south-eastern Australia (van Oldenborgh et al. 2021). In other cases, *compounding* disturbance interactions may occur whereby two disturbances occurring in close succession produce synergistic ecological responses (Paine et al. 1998; Simard et al. 2011) that can affect processes including succession (Pulsford et al. 2016). For instance, repeated high-severity fires at short intervals may pose an "immaturity risk" (Keeley et al. 1999) for serotinous trees that are precluded from reaching ecological maturity and the subsequent development of adequate seed stores. Similarly, recurrent fire in savannas suppress saplings, limiting their contribution to tree cover and sexual reproduction – a "fire trap" (Hoffmann et al. 2012). Herbivores may have broadly similar effects in savannas, leading to a "browse trap" (Staver et al. 2014).

Another important trap is a "landscape trap" in which natural and human disturbances produce young, flammable vegetation that is at increased risk of repeated re-burning at high severity, thereby precluding it from growing to older, less flammable and/or reproductively mature vegetation, and potentially leading to ecosystem collapse (Fig. 1) (Lindenmayer et al. 2011). A "Landscape trap" is an example of both a linked disturbance interaction (positive feedback loop between climate change, recurrent fire and increased flammability in regrowth forest), and a compounding disturbance interaction (compounding effect of fire, climate change and logging increasing flammability/risk of high-severity fire and biodiversity loss). The conceptual basis for landscape traps was first articulated over a decade ago, with a particular focus on the obligate-seeder montane ash forests of the Central Highlands of Victoria, south-eastern Australia (Lindenmayer et al. 2011). Since that initial theoretical work, further empirical, field-based evidence has emerged that reinforces the original conceptual proposition for a landscape trap in montane ash forests. This evidence includes new insights into feedbacks and interactions between stand age and flammability, fire frequency, and plant life history attributes. There is also increasing evidence for the potential development of landscape traps in other ecosystems. These include the wet forests of north-eastern Victoria and Tasmania (where rainfall can exceed 2000 mm per year) (Enright et al. 2015; Furlaud et al. 2021), tropical forests in South America (Cochrane and Laurance 2008), the obligate-seeding dry woodlands of south west Western Australia (where rainfall can be as low as 250 mm annually) (Gosper et al. 2018), and temperate forests in western North America (Zald and Dunn 2018), southern South America (Paritsis et al. 2015; Tiribelli et al. 2019), and New Zealand (Kitzberger et al. 2016). Part of this body of work includes evidence for, and discussions about, the risks of recruitment failure, growth, and survival posed by recurrent fire at short intervals (sensu 'Interval squeeze' syndrome (Enright et al. 2015; Turner et al. 2019)), and the potential for positive feedbacks associated with recurrent fire in flammable regenerating vegetation that can shift ecosystems into an entirely different stable states (e.g., Paritsis et al. 2015; Tepley et al. 2018). Other work on landscape traps has examined the influence of stand age on microclimate and inter-relationships with forest flammability (Furlaud et al. 2021).

Here we show quantitatively for the first time that a landscape trap has sprung in the montane ash forests of mainland south-eastern Australia; vegetation communities which include the world's tallest flowering plants (Ashton 1975). Montane ash forests are dominated by tall obligate seeding eucalypt trees comprising either Mountain Ash (*Eucalyptus regnans*) or Alpine Ash (*Eucalyptus delegatensis*) with the former approaching 100 m tall (Ashton 1975). They typically occur in very wet and mesic montane environments (Lindenmayer et al. 1996) and grow rapidly after germination, adding 1 m in height annually for up to

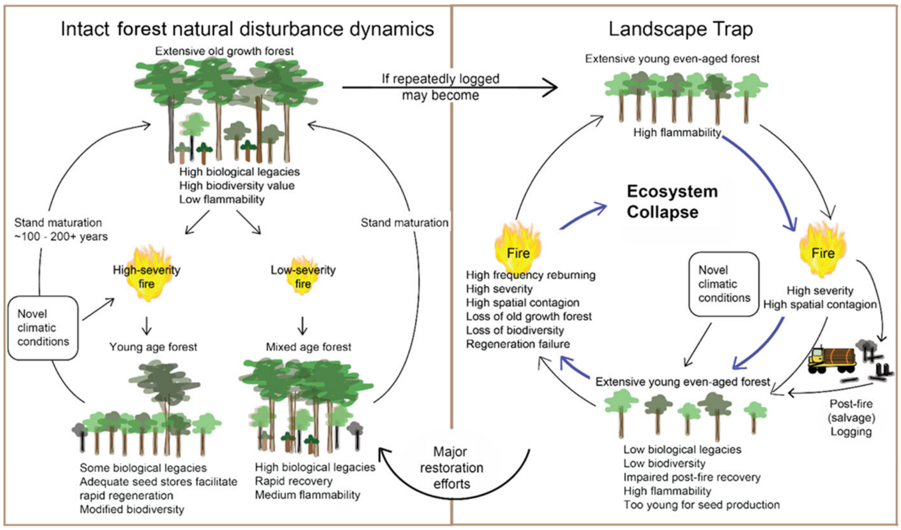


Fig. 1 Conceptual model of the interactions between disturbances, stand conditions, and life history attributes giving rise to a landscape trap (right side of the diagram) in comparison with a natural intact montane ash forest (left side of the diagram). The dark blue lines correspond to reburning of already young (and highly flammable) forest eventually resulting in ecological collapse if fire were to occur in stands that are too young for viable seed production occurs (see text). The conceptual model highlights the different frequency and combinations of disturbances in intact versus trapped forests

the first 70 years of life. Both Mountain Ash and Alpine Ash are typically killed by high-severity wildfires and regenerate from seed shed from the canopy at the time of a conflagration (Ashton 1975). Mountain Ash trees support epicormic buds, but have weak resprouting ability, possibly because the species dedicates resources to rapid growth in height at the expense of increasing bark thickness that would otherwise protect epicormics structures (Waters et al. 2010). Both Mountain Ash and Alpine Ash tree species also have delayed reproductive maturity with individuals that are less than 20–30 years old typically failing to produce sufficient viable seed to regenerate new stands in the event of a high-severity wildfire (Smith et al. 2013).

In this paper, we outline key pre-conditions for a landscape trap in montane ash forests and then present a new conceptual model demonstrating how it was triggered. We describe the significant implications of a landscape trap for forest logging, ecosystem service provision (e.g., water yields and carbon storage), and biodiversity conservation. We also discuss some approaches to landscape restoration that might help to rectify problems such as increased fire proneness, regeneration failure, and biodiversity loss created by a landscape trap in montane ash forests. We argue that it will be important to document evidence of the development of landscape traps in other vegetation types globally (e.g., Gosper et al. 2018; Tiribelli et al. 2019), especially where there may be interactions between human and natural disturbances (Cochrane and Laurance 2008; Furlaud et al. 2021).

Methods

Background

A landscape trap has developed in forests dominated by Mountain Ash and Alpine Ash trees (collectively termed montane ash forests) in Victoria, Australia. These forests are often even-aged, having regenerated after stand-replacing wildfires or clearcutting (Lindenmayer et al. 2019a, b). Fire is essential for natural regeneration in these forests, with the mean fire interval being 75–150 years (McCarthy et al. 1999). These obligate-seeder tree species are often killed in high-severity fires and regenerating trees do not produce viable seed until 20 to 30 years of age (von Takach Dukai et al. 2018). If repeated high-severity fires were to occur at intervals <20–30 years, these forests would be replaced by non-ash forest vegetation like *Acacia* spp. woodlands and grasslands (Photo 1) (Lindenmayer et al. 2011). This would have major impacts on carbon storage, water production, and biodiversity conservation (Lindenmayer et al. 2011).

Analyses

Throughout this article we refer to empirical studies that provide evidence that the pre-conditions of a landscape trap have been met in the montane ash forests of Victoria. Specifically, these studies quantified the following: (1) stand age-fire severity relationships and spatial dependence (Taylor et al. 2020, 2014), (2) the extent of loss of old-growth forests (Lindenmayer and Taylor 2020a), and (3) the probability of forests reaching reproductive maturation (Enright et al. 2015; von Takach Dukai et al. 2018).

Stand age-fire severity relationships and spatial dependence in fire severity in montane ash forests were quantified using a statistical analysis of fire damage at 9934 sites, following the 2009 wildfires in the Central Highlands of Victoria (Taylor et al. 2020, 2014).

Stand age-fire severity relationships and spatial dependence also were quantified for the 2019–20 wildfires by analyzing 33,850 grid points spaced at 500-m intervals across a 988,854-ha section of the fire footprint (Lindenmayer et al. 2021) (Appendix 1).

Data layers sourced from the Victorian Government were used to map temporal changes in the extent of old-growth in the Wet and Damp Ecological Vegetation Class [EVC] (which encompass Mountain Ash and Alpine Ash forests) from 1995 to 2020 (Lindenmayer and Taylor 2020a) as well as the frequency of fire in different EVCs (Lindenmayer and Taylor 2020b). These analyses revealed there has been a highly significant amount of disturbance to the old-growth forest estate in Wet and Damp Ecological Vegetation Class across Victoria in the past 25 years. This has occurred as a result of wildfires and logging operations (Lindenmayer and Taylor 2020a).

Finally, work by (Cary et al. 2021) analyzed three fire regime distribution models (Exponential, Olsen's, and moisture distributions) to compute the probability of forests reaching an old-growth stage (180 years), sawlog age (80 years), and reproductive maturity (for seed production, ~ 20 years) (Appendix 2).

Photo 1 Examples of the replacement of montane ash forest ▶ with stands of *Acacia* spp. woodland and grassland: **A** Toorongo Plateau, southern Victoria (Landsat 4–5 TM data, 1998, 2007). **A** The grassland areas (circled) replaced former montane ash stands following successive fires in 1926 and 1932 prior to the 1939 wildfires. This satellite image was taken on April 11 1988, ~ 49 years following the 1939 wildfires. The area was subsequently planted with Shining Gum (*Eucalyptus nitens*) trees by the Victorian Forestry Commission (McKimm and Flinn 1979). **B** Young flammable stand of Alpine Ash forest. This area has been subject to three fires since 1995, and is characterized by a complete absence of natural germination of overstorey tree seedlings following the last major wildfire in 2020 (Photo by R. Lindenmayer). **C** Young logged and regenerated Mountain Ash forest that was then burned at high severity in 2009. Subsequent plant surveys at this site over the past decade have revealed that the overstorey eucalypt trees have not germinated

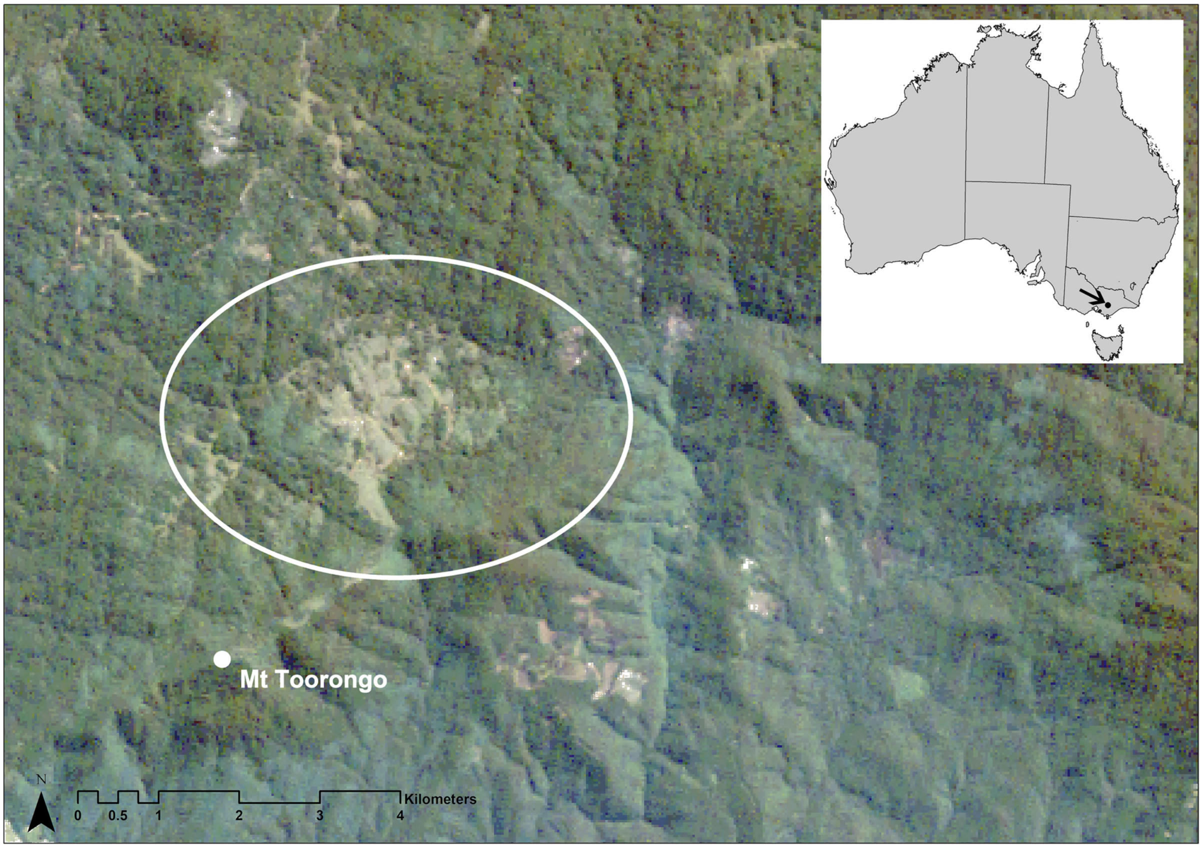
Necessary pre-conditions for a landscape trap

Three inter-related pre-conditions drive landscape trap development. These are as follows: (1) Stand age-fire severity relationships in which, relative to old-growth stands, young forests are more flammable and are at significantly greater risk of burning at high severity (which kills entire stands of overstorey trees). (2) Widespread young flammable forests (and rarity of less prone to high-severity fire, old-growth forests), leading to high levels of spatial contagion in elevated, high-severity fire. And, (3) Repeated fire at short intervals which can, in turn, interact with key life history attributes such as seed production to reduce or eliminate natural stand regeneration. Below, we present evidence that montane ash forests meet these necessary pre-conditions for a landscape trap. Importantly, the simultaneous expression of all three pre-conditions can be critical for a landscape trap to be sprung (see Fig. 1).

Pre-condition #1: stand age-flammability relationships

Climate and extreme fire weather are key drivers of fire ignition, behavior, and frequency (Jones et al. 2020; van Oldenborgh et al. 2021), but forest attributes like stand age and composition also affect fire severity

(a)



(b)

(c)

Photo 1 continued

(Tiribelli et al. 2019; Zald and Dunn 2018; Zylstra et al. 2016). A pre-condition for a landscape trap is that young, forest stands exhibit markedly higher levels of high-severity fire relative to older stands – a phenomenon observed in several vegetation types globally (e.g., Furlaud et al. 2021; Gosper et al. 2018; Taylor et al. 2014; Tiribelli et al. 2019; Zald and Dunn 2018). Increased flammability may be explained by several inter-related mechanisms, such as crown-density, plant architecture, and specific plant-traits within species or groups of species (Pausas et al. 2017; Zylstra et al. 2016). For instance, some plant life-forms that occur at high densities in young montane ash forests (Bowd et al. 2021) have been associated with an increase in flammability (e.g., some graminoids, *Acacia* and shrub species) (Cadiz et al. 2020; Tumino et al. 2019; Zylstra et al. 2016).

Analysis of wildfires in montane ash forests in 2009 contained evidence of a left-skewed, non-linear, relationship between stand age and fire severity (as reflected by the probability of a crown burn, Fig. 2a) (Taylor et al. 2014). This work showed that (after controlling for fire weather), young montane ash forests aged $\sim$ 10–40 years were subject to elevated fire severity, with the lowest levels of severity in old-growth stands (exceeding 120 + years) (Taylor et al. 2014). Work by Attiwill et al. (2014) showed broadly similar patterns to those found by Taylor et al. (2014). There also were high levels of spatial dependence in wildfires burning in landscapes dominated by young forest in the 2009 fire (Taylor et al. 2020). That is, young stands close together (e.g., $\sim$ 200 m) were significantly more likely to burn (and burn at similar levels of fire severity) than those located a long way apart (>10 km). Notably, a study by Cruz et al. (2012) of fire behavior showed that the 2009 conflagration burned as a rapidly spreading crown fire through young forest until it encountered old montane ash forest, where fire severity decreased.

A second study of stand age-fire severity relationships was completed following the 2019–20 fires in the Wet and Damp EVC (which encompass Mountain Ash and Alpine Ash forests) in north-eastern Victoria (Appendix 1). The best supported model from these statistical analyses (identified using the Widely Applicable Information Criteria [WAIC] (Vehtari et al. 2017)) for the probability of a Crown Burn revealed a three-way interaction between fire weather, forest type, and stand age (Lindenmayer et al. 2021). As in the case of analyses of the 2009 wildfires, there was a non-linear, negative polynomial stand age-fire severity relationship, with the probability of a Crown Burn generally low in very old forest and very young forest (see Fig. 2b). Similar to the 2009 fire, there also was a high level of spatial dependence between burnt areas in the 2019–20 wildfires in these forests (Lindenmayer et al. 2021) (see Appendix 1). While the evidence that young montane ash forests are susceptible to high-severity wildfire is compelling (Lindenmayer et al. 2021; Taylor and Lindenmayer 2020; Taylor et al. 2014), other kinds of evidence suggest that older forests are more likely to experience lower severity fire (Lindenmayer et al. 1999). For example, old-growth montane ash stands are almost never comprised of a single age cohort of overstorey trees, but typically support multiple age classes (Lindenmayer et al. 2000), with many of these trees supporting fire scars (Lindenmayer et al. 1991). This condition suggests that old-growth stands can experience multiple lower severity wildfires (Banks 1993; Lindenmayer et al. 1999) that does not kill all of the large old trees they support (McCarthy and Lindenmayer 1998). Moreover, these forests are typically characterized by a lower abundance of species associated with an increase in flammability (e.g., graminoids, shrubs, *Acacia*), and a higher occurrence of potentially less-flammable plant species including tree-ferns (Blair et al. 2016; Cawson et al. 2018).

Pre-condition #2: extensive young fire-prone forest

A second pre-condition for a landscape trap is that an ecosystem must be dominated by young forest (with elevated flammability and high risk of reburning, Fig. 2). Spatial analyses of forest cover and fire frequency data indicate that old-growth in the Wet/Damp Ecological Vegetation Class (EVC) is now very rare across Victoria due to recurrent fire and widespread logging (Lindenmayer and Taylor 2020a). Approximately 85% of this EVC that was formerly old-growth in 1995 has been heavily disturbed by either fire or logging in the past 25 years (Lindenmayer and Taylor 2020a). One of the key regions for this EVC is the Central Highlands of Victoria, where only 1.16% of Mountain Ash forest is now old-growth or 1/30th–1/60th of what it was historically (prior to 1900) (Lindenmayer and McCarthy 2002). Similarly, 0.47% of Alpine Ash forest in the region is old-growth (Lindenmayer and Taylor 2020a), although its historical extent is unknown. Importantly, not only is the extent of loss of old-growth pronounced, but remaining old-growth patches are small and fragmented (Photo 2). For example, the current remaining 1886 ha of old-growth Mountain Ash forest (of a total 171 400 ha in the Central Highlands region) is distributed across 147 individual patches (Lindenmayer et al. 2012) (Fig. 3).

Reconstruction work based on the diameter of large old remnant dead trees in now young regrowth stands suggests that between 30% and 60% of the Mountain Ash forest estate was previously old-growth forest (Lindenmayer and McCarthy 2002). Therefore, historical patterns of forest cover at the landscape scale, where previously small patches of regrowth forest were once embedded within a matrix of extensive old-growth forest, have now been reversed (Photo 2). That is, old-growth forests are now small patches in a matrix of extensive young, regrowth forest. Indeed,

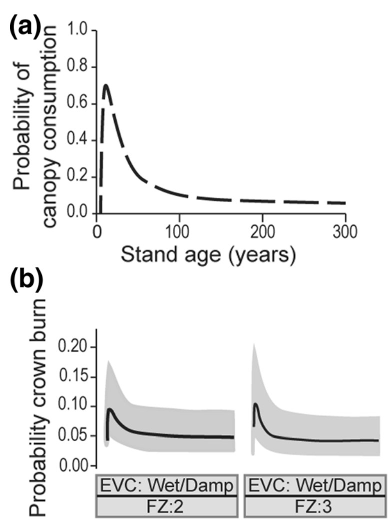


Fig. 2 Left-skewed relationship between fire severity and stand age in: A. Mountain Ash forests burnt in 2009 (modified from Taylor et al. (2014)). The measure of fire severity is the probability of canopy consumption. B. Wet and Damp Ecological Vegetation Class forests (which includes Alpine Ash) burnt in northeastern Victoria in 2019–20 (Lindenmayer and Taylor 2020a; Lindenmayer et al. 2021). The two components of diagram B correspond to forests burnt at high severity (leading to a crown burn) under extreme fire weather [FZ2 (fire zone 2) and FZ3 (fire zone 3)] when the Forest Fire Danger Index was at catastrophic levels. Shaded areas correspond to 95% credible intervals in the models (see Lindenmayer et al. (2021) for further details)

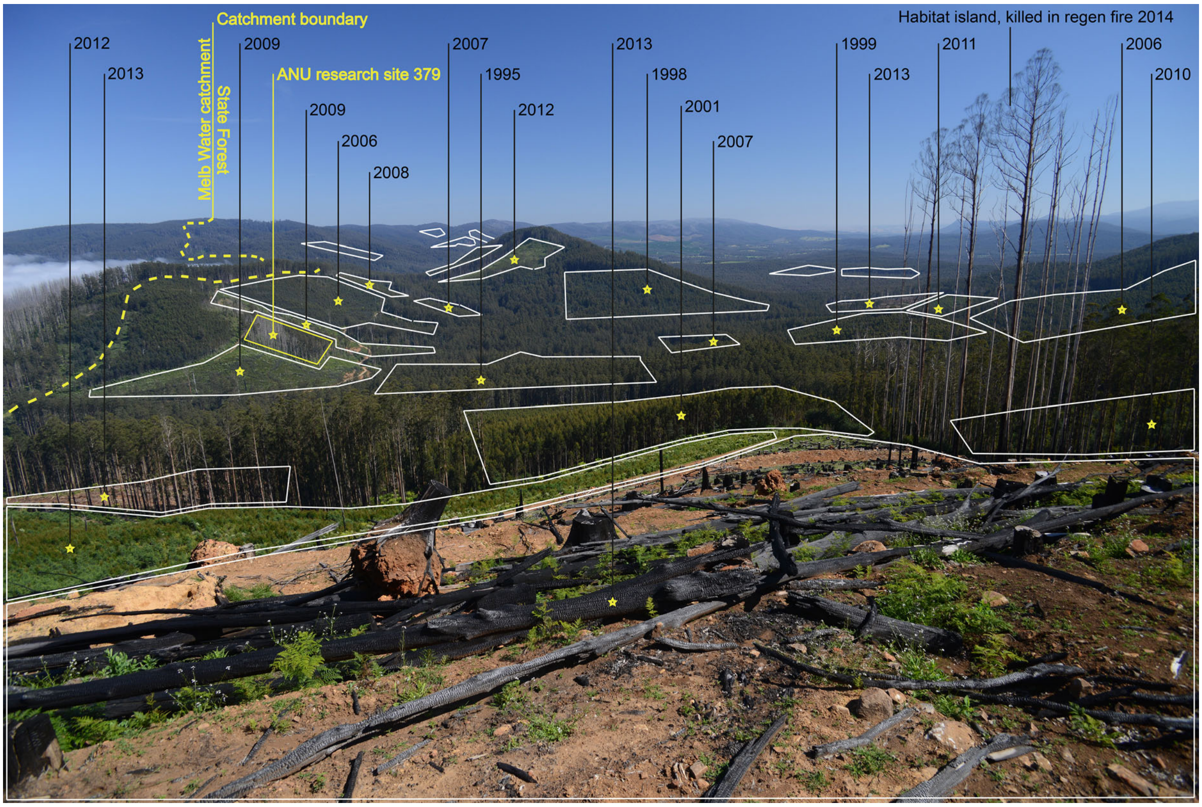


Photo 2 Extensive disturbed and then regenerated young regrowth montane ash forest in the Central Highlands of Victoria. The white lines mark the boundaries of recently cut areas (as denoted by the year of clearcut logging; Photo by Dave Blair). This 4000 ha landscape includes 24 ha of old-growth forest

approximately 99% of montane ash ecosystem in regions such as those in the Central Highlands of Victoria is young forest. Moreover, the flammability of extensive areas of young forest (see pre-condition #1), coupled with the spatial contagion of such fires, means that high-severity fires can destroy adjacent small patches of old-growth forest (Photo 3). Indeed, this problem is underscored by the fact 70% of montane ash forests across the Central Highlands region of Victoria has been either severely disturbed by high-severity fire or logging in the past 20 years or is within 200 m from a severely disturbed area (Taylor and Lindenmayer 2020). However, the size of old-growth patches required to depress fire severity relative to the high-severity characteristic of surrounding young stands remains unknown.

Finally, fire regime distribution modeling indicated that the probability of forests becoming old-growth stands and developing adequate hollow-bearing trees ($\sim$ 180 years) is predicted to be as low as 0.03 (3% of fire intervals) under a future fire regime (Cary et al. 2021). In addition, only one in five future fire intervals will be sufficiently long enough ($\sim$ 80 years) to grow sawlogs in Mountain Ash forests (Cary et al. 2021).

Pre-condition #3: repeated fire at short intervals

Consistent with pre-condition #3 for the development of a landscape trap, the incidence and extent of wildfire has been increasing significantly in the past 25 years (Lindenmayer and Taylor 2020b), with Wet and Damp EVC heavily impacted (Bowman et al. 2014). Some areas have burnt up to four times since 1995, with the inter-fire interval as short as six years in some places (Lindenmayer and Taylor 2020a), whereas the pre-European fire return interval for high-severity stand-replacing fires was thought to be 75–150 years (McCarthy et al. 1999). Many of these areas have been subject to repeated high-severity conflagrations (Lindenmayer and Taylor 2020b;

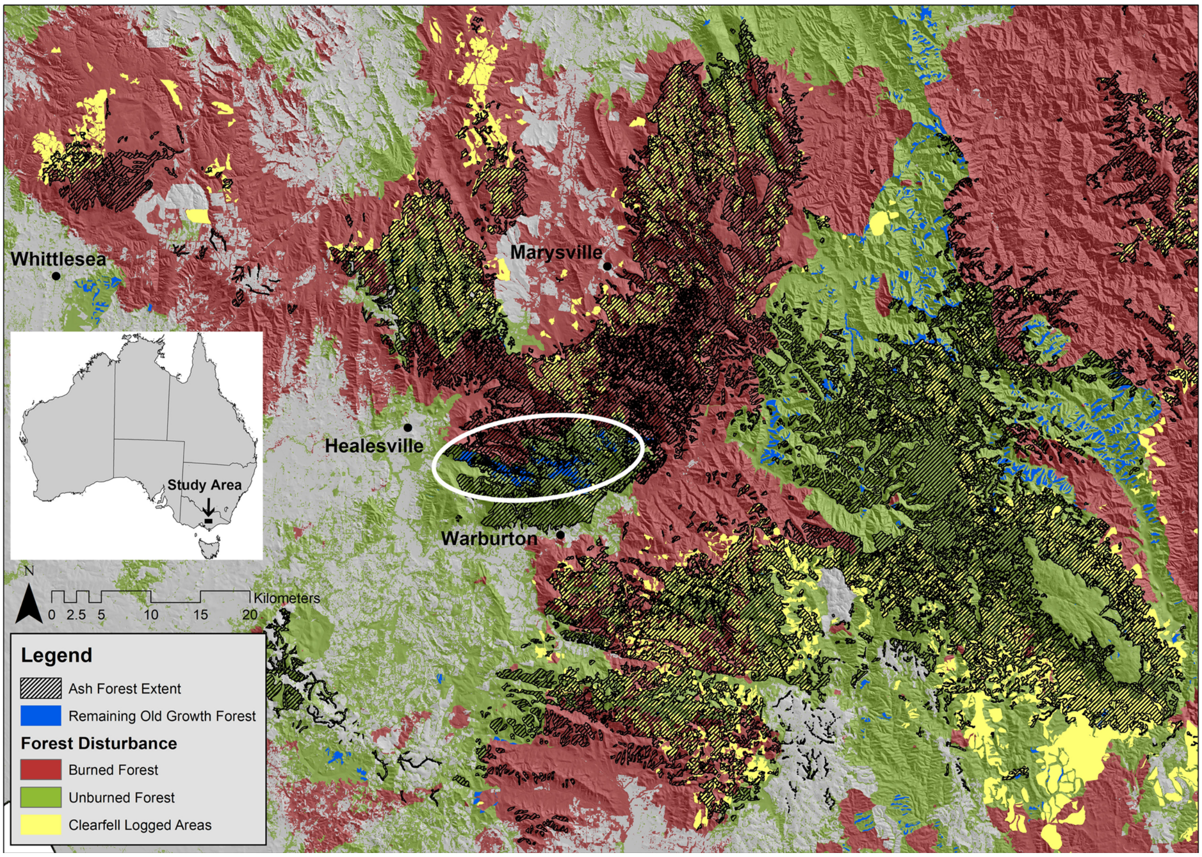


Fig. 3 The extent of fires and logging in montane ash forests in the Central Highlands of Victoria up to 2020 based on data provided by the Government of Victoria (see Lindenmayer and Taylor 2020a). Mapping analyses highlight the limited remaining unburned old-growth forest areas which are largely confined to a small cluster of patches (circled). Old-growth forest is defined as stands exceeding 250 years old based on the revised definition developed by the Government of Victoria (see Lindenmayer and Taylor 2020a)

Lindenmayer et al. 2021). In the case of the 155,055 ha of Alpine Ash mapped in State Forests by the Victorian Government, analyses of disturbance data (Department of Environment and Land and Water Planning 2021; Department of Sustainability and Environment 2007) shows that 84% of this forest type was burned between 1980 and 2020, with 34% burned by two or more fires (Appendix 3). Some regions dominated by Alpine Ash forest have been particularly heavily affected. For example, three high-severity fires burned Alpine Ash forests in the Carey River State Forest (located in Central Victoria) between 1998 and 2019 (Appendix 3). Following these fires, areas of Alpine Ash forest were subsequently clearcut (Appendix 3), resulting in four major disturbance events in these forests over a 20-year period.

In addition to structure-related changes in fuels and flammability in forests, climatic changes that increase fire activity (van Oldenborgh et al. 2021) will also be an important factor in the development of landscape traps. There has been marked drying and increases in temperature in our study area over the past few decades (e.g., see Cai and Cowan 2008). Hence, we recognize that for pre-condition #3 (as well as the other pre-conditions), there are both forest structure and flammability processes and climate-driven flammability processes contributing to the development of landscape traps.

Photo 3 A logged and regenerated forest that was burned and killed by a high-severity fire in 2009 with that fire also burning and killing an adjacent small patch of old-growth forest (Photo by Dave Blair)

Feedbacks and interactions between pre-conditions

Interactions among pre-conditions can be important for reinforcing the development of a landscape trap (Figs. 1 and 4). For example, repeated fire at short intervals precludes the recruitment of new stands of old-growth (pre-condition #2), while expanding the amount of flammable young fire-prone forest (pre-condition #1). Another feedback from interactions between pre-conditions is a rapid decline in biological legacies like large old dead trees. These trees are critical nest sites for cavity-dependent biota (Lindenmayer et al. 2017) and are most prevalent in old-growth forest (Lindenmayer et al. 2000). They are created when fires burn old-growth stands; with such trees then persisting for several decades in regenerating stands, facilitating colonization by cavity-dependent wildlife (Lindenmayer et al. 2019a, b). Large dead trees are not produced when young stands are burned repeatedly by high-severity fire, thereby eliminating suitable trees for occupancy by many taxa, including some of conservation concern (Lindenmayer et al. 2019a, b). In addition, large dead trees in regrowth forests are susceptible to being totally consumed in a subsequent wildfire (Lindenmayer et al. 2012) or at risk of rapid collapse when the surrounding stand is a young regenerating forest (Lindenmayer et al. 2016). Hence, a landscape trap can trigger major declines in biodiversity.

Post-fire (salvage) logging is another important kind of interaction between natural disturbance and human disturbance in montane ash forests (Lindenmayer et al. 2018) and can contribute to the development of a landscape trap. It can impair plant and animal species recovery, disrupt plant-soil-microbial feedbacks (Bowd et al. 2021), and result in major losses of key biological legacies (such as large old trees) (Bowd et al. 2018; Lindenmayer et al. 2019a, b). Moreover, salvage logging also interacts with pre-condition #1 resulting in high densities of flammable regrowth vegetation, with little structural diversity (Bowd et al. 2018; Lindenmayer et al. 2019a, b). Salvage logging occurred after the 1939, 1983, 2009 and 2019–2020 wildfires in Victoria (Bowd et al. 2018; Lindenmayer et al. 2008) (e.g., see https://www.vicforests.com.au/fire-management-1/vicforests-starts-post-fire-timber-recovery). Such kinds of operations may increase concurrently with increases in

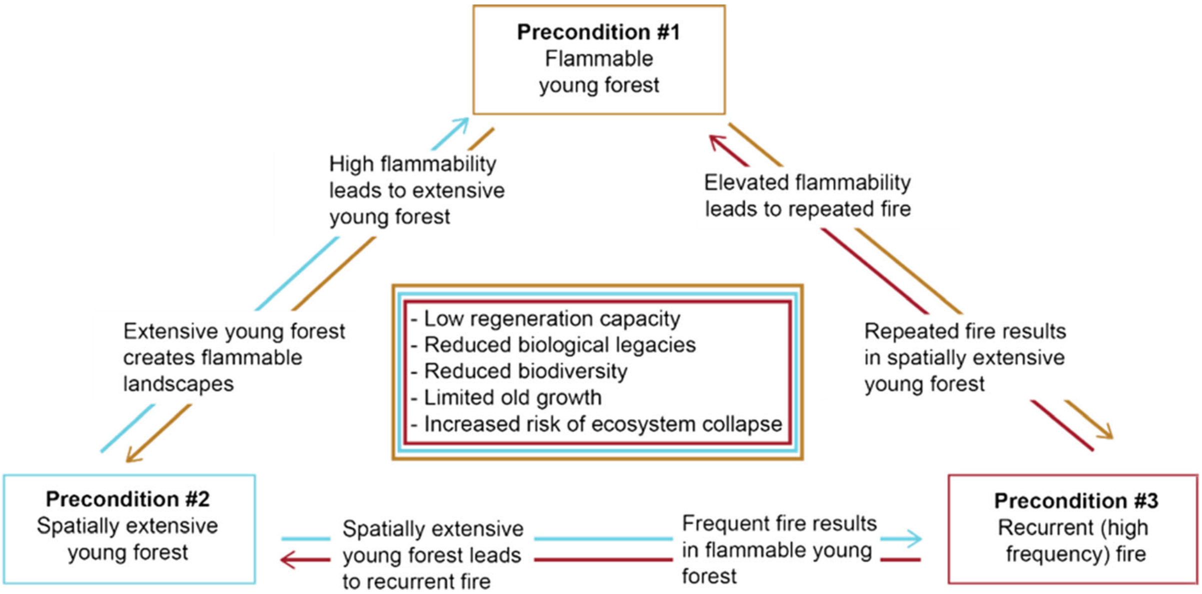


Fig. 4 Interactions among three key pre-conditions leading to a landscape trap in montane ash forests, with their conjoint impacts on stand regeneration, ecosystem services, biological legacies, biodiversity, and old-growth extent. Colors differentiate each of the three pre-conditions and the arrows demonstrate the interactions among them

high-severity wildfire, thereby reinforcing the development of a landscape trap (see Fig. 1).

A further problem with landscape traps is the interaction between recurrent disturbance and critical life history attributes of dominant trees, like the time required to develop adequate seed stores (Keeley et al. 1999), and seed dispersal which can be limited in surrounding young forests (Gill et al. 2021). The lowest rates of regeneration success occur where young stands have been burnt (Smith et al. 2016). Post-fire natural regeneration failure in montane ash forests is now widespread across Victoria (http://tiny.cc/u490tz). Efforts are underway to gather seed in an attempt to revegetate large areas of young forest that was burnt after recent wildfires but failed to recover (see Fig. 2c). When artificial seeding fails, montane ash stands will collapse (see Fig. 1) and will likely be replaced by *Acacia*-dominated woodland (Photo 1a and b) because *Acacia* produces large, long-lived stores of viable seed at an earlier age than eucalypts (Passos et al. 2017). Notably, in the past, extensive areas of montane ash forest spanning ~ 10 000 ha that were subject to recurrent wildfires suffered ecosystem collapse and became dominated by *Acacia* spp. and grasslands, with the area then artificially regenerated, in part, with non-native seed stock (see Photo 1) (McKimm and Flinn 1979).

Management implications

Our initial work on landscape traps (Lindenmayer et al. 2011) was a theoretical conceptualization of how they might develop and manifest. Since that time, new insights on stand age and flammability relationships, fire frequency, and other empirical studies indicate that the landscape trap in Victoria's montane ash forests has been sprung. The trap has significant resource management and conservation implications. First, the optimal age for trees to become sawlogs in these forests is > 80 years, but high frequency of reburning means that stands have ~ 80% probability of being burnt before this age (Cary et al. 2021) (Appendix 2). Logging industries therefore have highly uncertain access to millable timber. Second, the rarity of old-growth forest (Lindenmayer and Taylor 2020a) will impair ecosystem service provision (e.g., carbon storage and water yield) (Keith et al. 2017; Taylor et al. 2019), and erode habitat suitability for an array of threatened species (Lindenmayer et al. 2017). Moreover, ongoing climate change will increase future wildfire risk (Cary et al. 2012; Jones et al. 2020; van Oldenborgh et al. 2021) including in extensive areas of already young, highly flammable forest where fire severity is highest (Taylor et al. 2014), natural regeneration is lowest (Smith et al.

Photo 4 Old-growth montane ash forest. The ecologist in the red-shirt shows the size and height of the dominant trees (Photo by Esther Beaton)

2013), and biodiversity and ecosystems service values are impaired (Keith et al. 2017). Finally, the giant old trees (up to 100 m in height; Photo 4) characterizing montane ash forests (Lindenmayer et al. 2000) may become a thing of the past as the landscape trap continues to preclude the recruitment of old-growth forest.

In addition to the effect of climate change on fire regimes in areas that support montane ash forests (Cary et al. 2021, 2012), there also may be direct impacts of climate change on tree demographics such as reduced tree height and tree size (see Clark et al. 2021), slower rates of growth and an increased juvenile period, reduced germinant establishment and survival (Hoyle et al. 2013), and impaired seed production (Enright et al. 2015). All of these factors may contribute to the development and subsequent long-term maintenance of landscape traps. Moreover, montane ash forests occupy a relatively narrow range of bioclimatic conditions (Lindenmayer et al. 1996) and anticipated changes in climate may make current locations where these ecosystems occur environmentally unsuitable for them within the next 50 years (VEAC 2017).

"Unspringing" the landscape trap: strategies for ecosystem restoration

Substantial policy and management interventions will be required to reverse the problems that have arisen from the development of a landscape trap in montane ash forests. First, these ecosystems have experienced a large amount of recurrent disturbance at frequent intervals. It is therefore important to reduce the number of stressors in montane ash ecosystems, particularly ones which are relatively straight forward to manage such as the extent and amount of logging. Reducing the amount of logging will reduce the rate at which further areas of young, fire-prone forest is added to already highly fire-prone and extensively fragmented ecosystems (Taylor and Lindenmayer 2020). It also will reduce the risk of depleting seed sources needed to facilitate reforestation in the event of future fires. A critical component of reducing the number of stressors in montane ash ecosystems, will be to recognize that some widely recommended strategies to reduce fire severity such as commercial thinning (e.g., Volkova et al. 2017) may in fact have limited effectiveness, and can sometimes, elevate the severity of subsequent wildfires (Taylor et al. 2020, 2021).

Second (and related to the first recommendation), we suggest that new policies must attempt to expand the currently limited old-growth estate. Implementing such policies is an enormous challenge given changes toward a warmer and increasing dry climate in the south-eastern Australia (Cai and Cowan 2008; Cary et al. 2012). However, such an approach may have an increased chance of success if it is focused on more sheltered parts of landscapes where fire severity have generally been lower in the past (Lindenmayer et al. 1999) and ecologically mature forests have the highest probability of developing and persisting (Mackey et al. 2002). Third, given that montane ash ecosystems have been exposed to so many wildfires, often of very high severity (see Collins et al. 2021), new approaches to fire detection and suppression are required. These include integrating satellite imagery with data on ignition sources (e.g., lightning strikes for natural ignitions and/or road locations/human population density for human ignitions), and the use of detection and suppression technologies like drone detection and unmanned autonomous vehicles. These approaches may provide important opportunities to rapidly extinguish ignitions before they become major conflagrations (Roldán-Gómez et al. 2021).

Concluding comments

Feedbacks between natural and human disturbances can produce various kinds of traps in ecosystems. An important kind of trap is a "landscape trap" in which natural and human disturbances such as fire and logging produce young, flammable forests at increased risk of repeated re-burning at high severity, thereby precluding them from growing to ecological maturity. Subsequent to initial theoretical work on landscape traps (Lindenmayer et al. 2011), further empirical, field-based evidence has emerged that reinforces the original conceptual proposition for their development. We have presented new empirical evidence that shows that a landscape trap has been sprung in the tall, wet, montane ash forests in mainland southeastern Australia. The trap has been sprung because three key preconditions for its development have been met. These include the prevalence of widespread flammable young forest and repeated high-severity fire, which interact to place the ecosystem at high risk of collapse. Historical patterns of forest cover have now been altered from widespread old-growth forest with small patches of regrowth embedded within it, to the reverse.

Landscape traps such as the one that has been sprung in montane ash forests have significant ecological and resource management implications. Key restoration interventions such as strategic expansion of old-growth forests and a reduction in the number of disturbance stressors in montane ash forests will be required to reverse the problems associated with springing a landscape trap in montane ash forests.

Finally, we argue it is critical that an examination be conducted globally of the risk of landscape traps developing in other ecosystems (e.g., Furlaud et al. 2021; Gosper et al. 2018; Odion et al. 2004; Tepley et al. 2018; Zald and Dunn 2018) including those at risk of regeneration failure under short fire return intervals (e.g., North-American subalpine lodgepole pine forests (Turner et al. 2019) and Canadian conifer forests (Brown and Johnstone 2012; Buma et al. 2013)). This examination should include forests subject to multiple stand-replacing disturbances that can interact and influence the extent and frequency of the other disturbances, as well as interact with life history attributes, thereby compounding ecological impacts (e.g., Thompson et al. 2007; Tiribelli et al. 2019; Zald and Dunn 2018).

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Declarations

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