

Principles and practices for biodiversity conservation and restoration forestry: a 30 year case study on the Victorian montane ash forests and the critically endangered Leadbeater's Possum

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ABSTRACT

We present a detailed case study of conservation and restoration of the Australian arboreal marsupial Leadbeater's Possum (*Gymnobelideus leadbeateri*) and its Mountain Ash forest habitat to illustrate the important intersection between forest restoration principles and the general principles for forest biodiversity conservation. Mountain Ash forests have been extensively modified through a century of intensive logging, recurrent wildfires and post-fire salvage logging. These disturbances have led to a reduction in old growth forest to 1/30th-1/60th of the extent of historical levels, a rapid collapse followed by a prolonged (>30-year) shortage of populations of hollow-bearing trees throughout the Mountain Ash forests (which are critical habitat elements for many species of cavity-dependent vertebrates), and an increased risk of re-burning of landscapes dominated by young, regrowth forest. The consequences of the severe decline and consequent 'temporary extinction' of large old trees will be the potential global extinction of Leadbeater's Possum whose distribution is significantly associated with the number of large old trees. We outline the conservation and forest restoration principles and practices that are needed to address these problems. We discuss how general principles for forest restoration must be multi-faceted and multi-scaled by encompassing strategies ranging from retaining existing key residual elements of original natural forest cover (e.g. remaining populations of target species, key structures, habitats, and patches) through to restoring patterns of forest cover and key ecosystem processes. We also outline how forest restoration principles intersect strongly with similarly multi-faceted and multi-scaled general principles for forest biodiversity conservation – in particular, those corresponding to conserving populations of particular species and their habitats, maintaining stand structural complexity, maintaining patterns of landscape heterogeneity, and perpetuating key ecosystem processes. Finally, we outline the potential for positive cumulative benefits of multiple restoration and conservation strategies by outlining how actions at one scale can create benefits at other (smaller or larger) scales.

Key words: Leadbeater's Possum, Mountain Ash forest, Victoria, logging, wildfire, forest conservation principles, forest restoration principles, reserves

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Introduction

Forests are major repositories of biodiversity and are among the most species-rich environments on earth (World Commission on Forests and Sustainable Development 1999; Millennium Ecosystem Assessment 2005). Forest clearing and recurrent logging means that conserving forest biodiversity remains a major challenge for ecologically sustainable natural resource management (Gustafsson *et al.* 2012). Lindenmayer and Franklin (2002) argued that the conservation of forest biodiversity should be underpinned by a suite of general principles including:

1. Protecting populations of particular key species and overall diversity;
2. Conserving special vegetation communities, habitats and places (e.g. caves);
3. Maintaining the structural complexity of stands;
4. Maintaining landscape heterogeneity; and
5. Perpetuating key ecosystem processes.

Lindenmayer and Franklin (2002) further argued that effective implementation of these principles demanded

multi-faceted and multi-scaled approaches ranging from actions targeting the management of individual trees through to the protection of large ecological reserves at a regional spatial scale. These general principles were designed for forests that were largely intact, or at least not extensively modified by human disturbance (Lindenmayer *et al.* 2006). But what happens when a forest ecosystem has been heavily modified? – as is the case for over 2 billion hectares of extensively degraded natural forest worldwide – an area equivalent to the land masses of the USA, Australia and India combined (World Resources Institute 2011). Where forests are highly degraded, protection alone is insufficient and forest restoration is critical to allow them to regain their conservation value (Chazdon *et al.* 2009; Edwards *et al.* 2010). In such cases, two additional principles are required:

6. Proactively restore those elements of forest biota and attributes of forest structure and forest cover that have been depleted; and
7. Address the threats and processes which have led to forest degradation (e.g. Lamb 2011).

In this paper, we argue there is an important intersection between forest restoration principles and the general principles for forest biodiversity conservation (Hobbs *et al.* 2011) that have been developed for relatively intact areas of natural forest. We underscore these inter-relationships using a detailed case study of biodiversity conservation and forest restoration in the Mountain Ash (*Eucalyptus regnans*) forests of the Central Highlands of Victoria, south-eastern Australia. These forests have been extensively altered by over a century of high-intensity logging, repeated wildfires, and a combination of both fire and logging (i.e. salvage logging). We discuss the approaches needed to achieve the restoration of this extensively modified forest ecosystem, focussing in particular on the restoration of viable populations of the globally endangered Leadbeater's Possum (*Gymnobelideus leadbeateri*), which is a flagship species in this ecosystem and whose distribution is strongly associated with Mountain Ash forest (as well as other wet eucalypt forests such as those dominated by Alpine Ash (*Eucalyptus delegatensis*) and Shining Gum (*Eucalyptus nitens*)). These approaches to forest restoration are multi-scaled and multi-faceted and we outline explicit recommendations to: (1) conserve existing populations of Leadbeater's Possum as well as existing key structures and habitats for the species, (2) increase populations of the species, key elements of stand structure and areas of suitable habitat, and expand the cover of old growth forest, and (3) restore key ecosystem processes that drive the structure and cover of forest environments. Our case study on the intersection between forest restoration principles and general principles for forest biodiversity conservation also highlights the critical inter-relationships between key ecological processes and spatial patterns of species distribution, key structures and vegetation cover.

Background—the ecology and recent history of Mountain Ash forest

Our case study focuses on the Mountain Ash forests of the Central Highlands region of Victoria, south-eastern Australia. The region is ~120 km north-east of the city of Melbourne and covers approximately half a degree of latitude and one degree of longitude (37°20'–37°55'S and 145°30'–146°20'E) (Figure 1). The Central Highlands supports ~121 000 ha of Mountain Ash forest. Approximately 20% of this area is in closed water catchments, parts of which are also managed as the Yarra Ranges National Park (Viggers *et al.* 2013). The remaining 80% of Mountain Ash forest is located in areas broadly designated for paper pulp and timber production (Macfarlane *et al.* 1998).

Mountain Ash forests have been the focus of detailed ecological study for more than 30 years (Lindenmayer 2009a) and this body of research underpins our case study. Before outlining the principles and practices for forest restoration, we first provide a summary of the key structures and processes in Mountain Ash forests and the current status of the ecosystem.

Wildfire as a major form of natural disturbance in Mountain Ash forests

Fire is the primary form of natural disturbance in Mountain Ash forest (Ashton 1981). Prior to European settlement, the fire regime was infrequent, severe wildfire that occurred in late summer (Ashton 1981). Such severe wildfires may be of sufficiently high intensity to kill almost all of the overstorey trees, which release seeds from their crowns that germinate as young regenerating stems of a uniform aged cohort (Ashton 1976). Lower severity fires can result in multi-aged stands when the fire stimulates a regeneration cohort but the fire intensity is insufficient to kill all overstorey trees (McCarthy and Lindenmayer 1998).

The effects of fire on stand structure are linked to the age of a forest at the time it is burned. Fire in an old growth forest will produce a pulse of large dead trees and fire-scarred living old trees that can provide nesting habitat for a suite of cavity-dependent species (Lindenmayer 2009a). Such habitat does not develop in young burned forest because small diameter trees do not remain standing long after they are burned and nor do they have the internal volume of wood capable of supporting suitably sized cavities (Gibbons and Lindenmayer 2002). Moreover, when the interval between stand-replacing disturbances is <20 years, which is the period required for trees to reach sexual maturity and begin producing seed (Ashton 1981), stands of Mountain Ash forest will be replaced by other species, particularly wattle (*Acacia* spp.) (Lindenmayer *et al.* 2011a). Under the Victorian *Flora and Fauna Guarantee Act 1988* (Government of Victoria 1988), “inappropriate fire regimes causing disruption to sustainable ecosystem processes and the resultant loss of biodiversity” are listed as a potential threatening process.

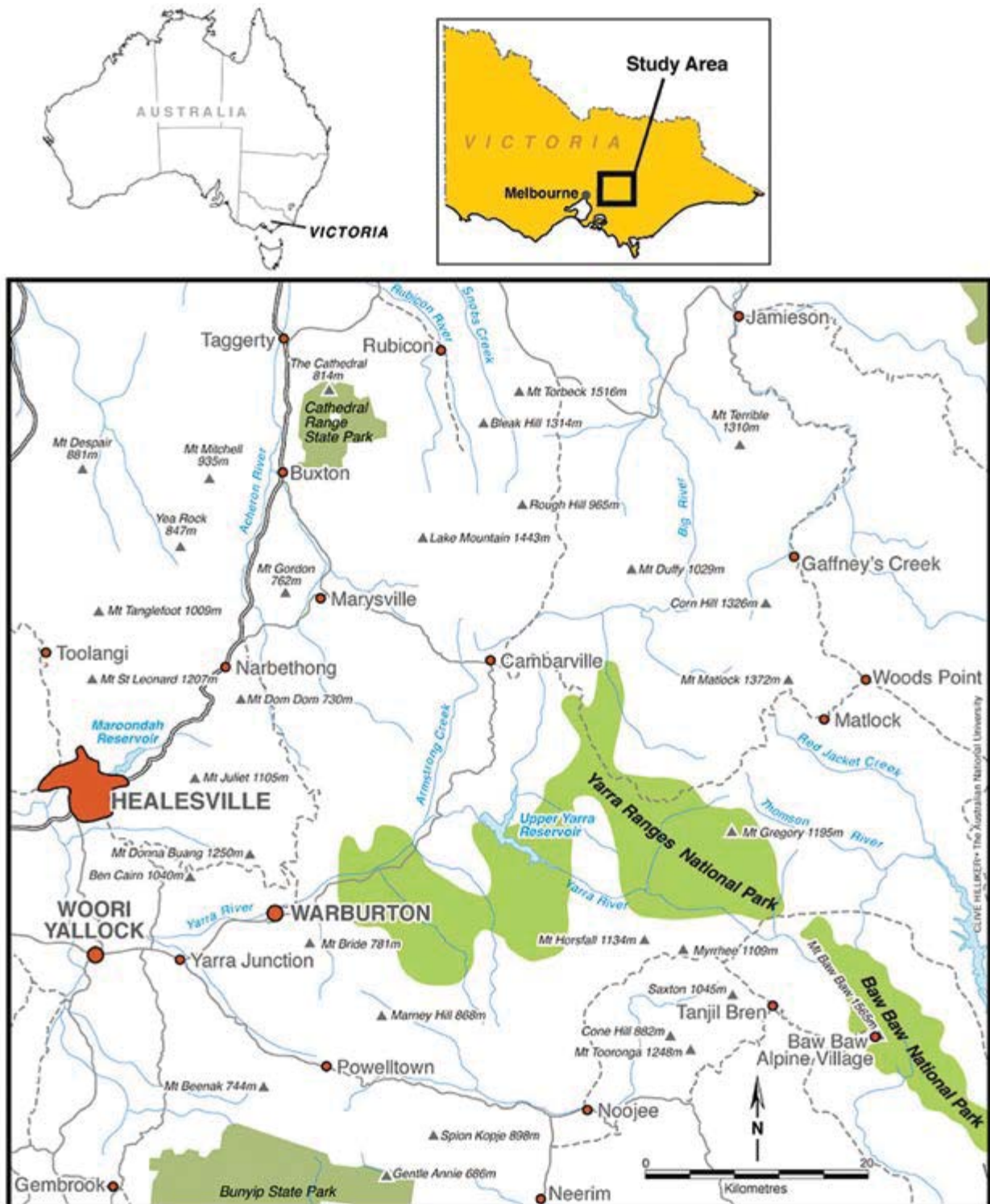


Figure 1. The location of the Central Highlands of Victoria. The area shown in the figure overlaps largely with the known distribution of Leadbeater’s Possum.

Logging as a major form of human disturbance in Mountain Ash forests

Logging is the primary form of human disturbance in Mountain Ash forests, and large areas have been subject to timber and pulpwood harvesting (Figure 2). Historically, more timber flowed through Port Melbourne than ports like Seattle in western North America, which have a far greater area than Melbourne

from which to source timber (Dingle and Rasmussen 1991). In the last 40 years, the conventional method of logging has been clearfelling in which all merchantable trees within a 15-40 ha area are cut in a single operation (Government of Victoria 2011). Following clearfelling, logging debris is burned to create a bed of ashes in which the regeneration of a new stand of eucalypts takes place, often by artificial reseedling (Flint and Fagg 2007).

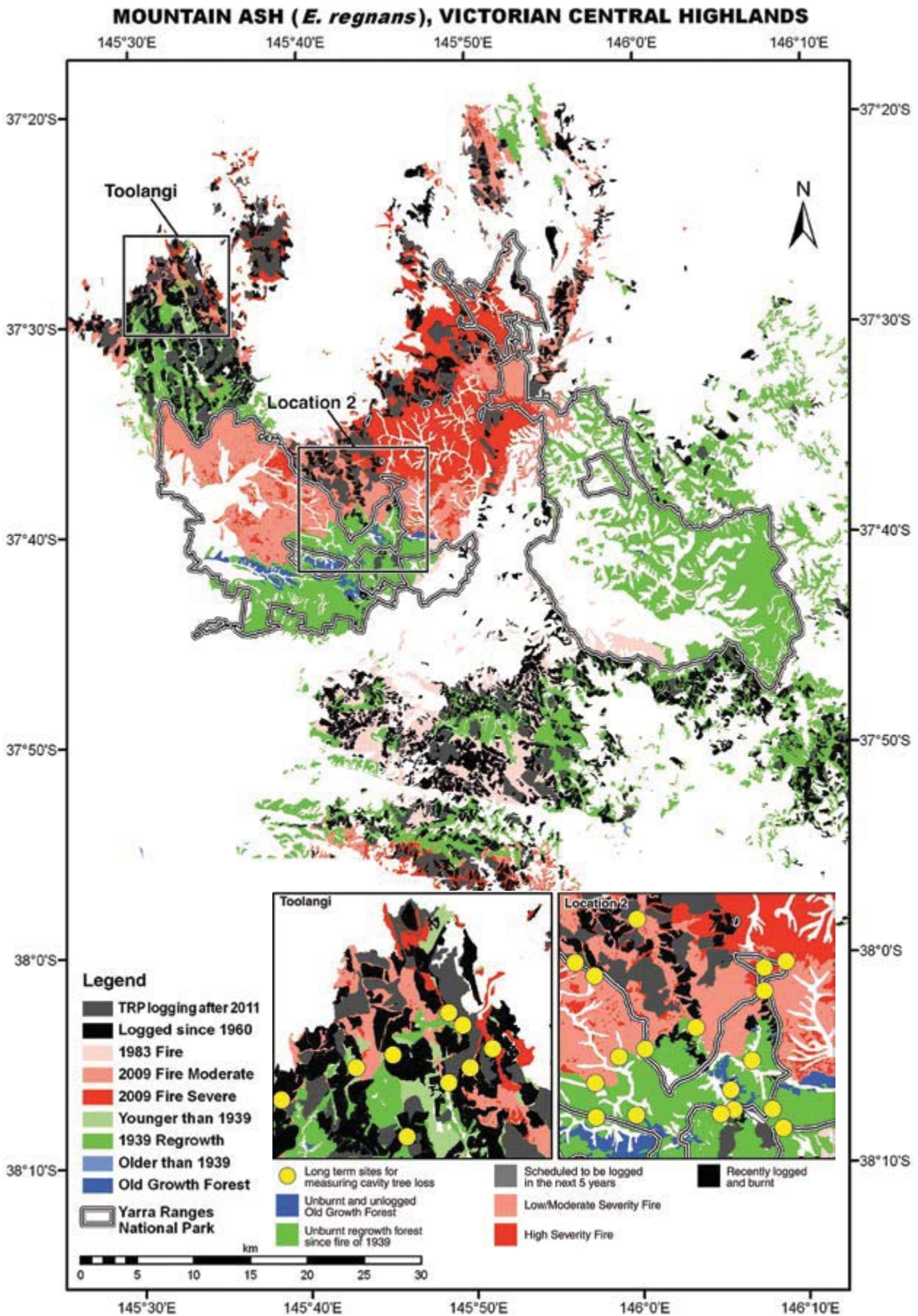


Figure 2. Overlaid maps showing the history of fire and logging in the Mountain Ash forests of the Central Highlands of Victoria. Redrawn from data layers sourced from the Government of Victoria and from Lindenmayer et al. (2012a).

An additional form of logging in Mountain Ash forests is post-fire salvage logging, sometimes called salvage harvesting. Salvage logging occurs when fire damaged stands are cut using conventional clearfelling (Lindenmayer and Ough 2006). Widespread salvage logging occurred after wildfires in 1939, 1983 and 2009 (Noble 1977; Lindenmayer and Ough 2006; Lindenmayer *et al.* 2010a).

Notably, logging operations in Victorian Mountain Ash forests are not profitable and the agency responsible for managing timber and pulpwood production (VicForests) is making significant financial losses (VicForests 2006-2012). Moreover, current rates of logging indicate that the remaining forest that could be logged will be completely cutover within the next 10-15 years. This is a result of many factors, including past levels of overcutting, losses of timber resulting from wildfires, and flawed current methods of calculating 'sustained yield', which is blind to the actual age of the forest, and assumes the whole forest to be of harvestable age. These factors ensure overcutting of remaining unburnt forest.

A key component of stand structural complexity - large old hollow-bearing trees and their importance for cavity-dependent species

Large old hollow-bearing trees are a key element of stand structural complexity in Mountain Ash forests. They provide irreplaceable shelter, nesting and denning sites for >40 species of cavity-dependent vertebrates, including Leadbeater's Possum (Lindenmayer *et al.* 1991c, 2011b), the Greater Glider (*Petauroides volans*), the Mountain Brushtail Possum (*Trichosurus cunninghami*) as well as threatened species like the Sooty Owl (*Tyto tenebricosa*) and the Yellow-bellied Glider (*Petaurus australis*). The probability of occurrence of several cavity-dependent species at a site is significantly related to the number of hollow-bearing trees on a site (Lindenmayer *et al.* 1991c, 1994, 2011b, 2013) (Figure 3). Large old trees also provide important sources of pollen and nectar for many species (Ashton 1975) as well as store large amounts of carbon (Keith *et al.* 2009).

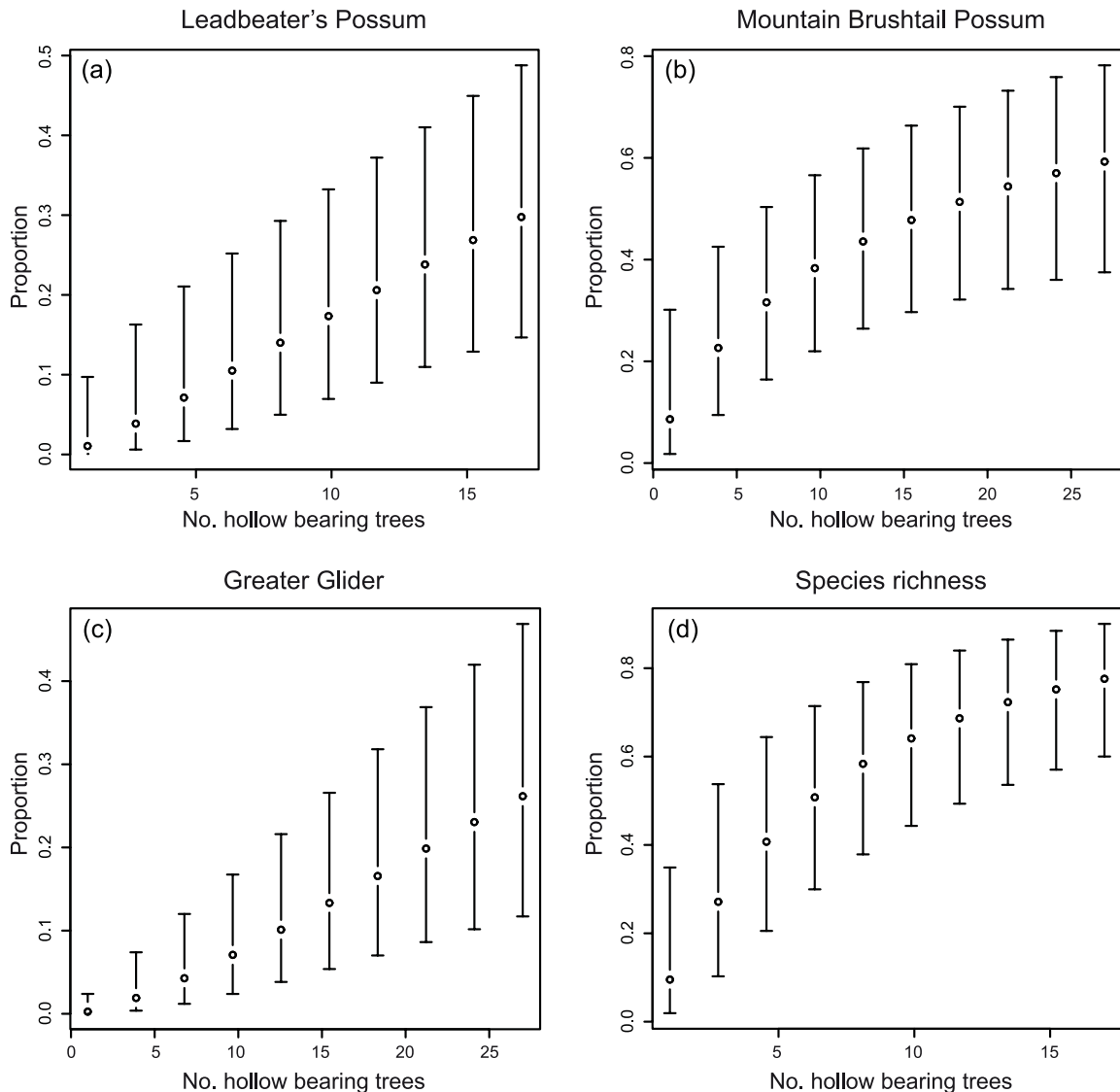


Figure 3. Relationships between the occurrence of arboreal marsupials and the number of hollow-bearing trees in the Mountain Ash forests. The relationships are based on composite datasets assembled from field studies conducted between 1983 and 2012.

Mountain Ash trees typically begin to develop cavities from approximately 120 years of age (Ambrose 1982; Lindenmayer *et al.* 1993b). Cavities are then a characteristic part of these trees for the remainder of their standing life of up to 550 years (Wood *et al.* 2010). The number of cavity-bearing trees is typically ~12-31 trees ha⁻¹ in old-growth stands of Mountain Ash forest (Lindenmayer *et al.* 2000).

Very rapid rates of death and collapse of large old Mountain Ash trees in the Central Highlands of Victoria occurred between 1998 and 2011 (Lindenmayer *et al.* 2012a). Of a sample of 1131 large old cavity-bearing trees, 39% collapsed, but no recruitment of new cavity-bearing trees occurred during this period. A pulse of tree loss occurred following major wildfires in 2009, which burned 34% of Mountain Ash forest in the region. On the burned sites, 79% of live cavity-bearing trees were killed and between 58-100% of large old dead trees were destroyed (i.e. consumed by the fire or collapsed within two years after the fire). The extent of consumption of old dead trees varied depending on their decay class and condition prior to the fire (Lindenmayer *et al.* 2012a). Elevated rates of tree mortality coincided with a severe drought, with 23% of large living trees dying on unburned sites between 2004 and 2011 (Lindenmayer *et al.* 2012a). Projections based on long-term data show a severe decline in large old trees from 5.1 ha⁻¹ in 1998 to ~0.6 ha⁻¹ by 2067 across the Mountain Ash forest estate (Figure 4) (Lindenmayer *et al.* 2012a). The projections highlight a 30-year absence of large old hollow-bearing trees between the time when most existing large old trees will have collapsed and when individuals in the next oldest cohort of trees (current 74-year old stands that regenerated after major wildfires in 1939) begin providing cavities (Figure 4).

The number of large old hollow-bearing trees is declining rapidly, not only because of fire and drought, but also because of logging operations (Lindenmayer *et al.* 2012a). Hollow-bearing trees have a high risk of being incinerated by high-intensity fires lit to regenerate logged stands (Lindenmayer *et al.* 1990). Retained trees on otherwise clearfelled sites also have a high probability of collapse because of exposure and wind-throw. These trees also suffer from accelerated rates of collapse in unlogged stands when adjacent areas of forest are logged due to increased wind-throw (Lindenmayer *et al.* 1997; Lindenmayer *et al.* unpublished data). The projections in Figure 4 do not include the rapidly accelerated losses of hollow-bearing trees that occur on logged sites (Lindenmayer *et al.* 1990), and within unlogged areas adjacent to logged sites (Lindenmayer *et al.* 1997). They also assume no fire until 2067.

The shortage of hollow-bearing trees in Mountain Ash forests will be ecosystem-wide because of repeated fires over the past 100 years combined with 40 years of widespread clearfelling. Together, these disturbances have resulted in 98.9% of the forest estate now being dominated by stands <74 years old. The consequences of the severe decline and consequent 'temporary extinction' of large old trees will be the potential global extinction of Leadbeater's Possum whose distribution is significantly associated with

the number of large old trees (Lindenmayer *et al.* 1991c, 2013) (Figure 3), and the ecosystem-wide loss of up to 40 other species of cavity-dependent vertebrates found in Mountain Ash forests (Lindenmayer 2009a). Notably, the loss of hollow-bearing trees is gazetted as a potential threatening process under the Victorian *Flora and Fauna Guarantee Act 1988* (Government of Victoria 1988).

Sensitivity of Leadbeater's Possum to disturbance

Detailed empirical studies have indicated that Leadbeater's Possum (and indeed several other cavity-dependent species) are highly sensitive to the effects of clearfelling and salvage logging. Significant negative long-term environmental impacts of clearfelling on forest structure and on biodiversity occur at both the stand and landscape scales (reviewed in Lindenmayer 1994, 2009a). For example, given that all overstorey trees are cut down on clearfelled sites, and that hollow-bearing trees take typically 120-190+ years to develop, areas that are logged can remain unsuitable habitat for cavity-dwelling species for up to two centuries (Lindenmayer 1994). Indeed, Leadbeater's Possum does not inhabit logged and regenerated Mountain Ash forest where no hollow-bearing trees have been retained (Lindenmayer 1994). In addition, this species is largely absent from linear strips of 40-80m wide unlogged forest that are retained between clearfelled blocks (Lindenmayer *et al.* 1993a).

Leadbeater's Possum is virtually absent from sites burned in the 2009 fires and the numbers of the species are also significantly depressed on unburned sites where the surrounding landscape has been burned (Lindenmayer

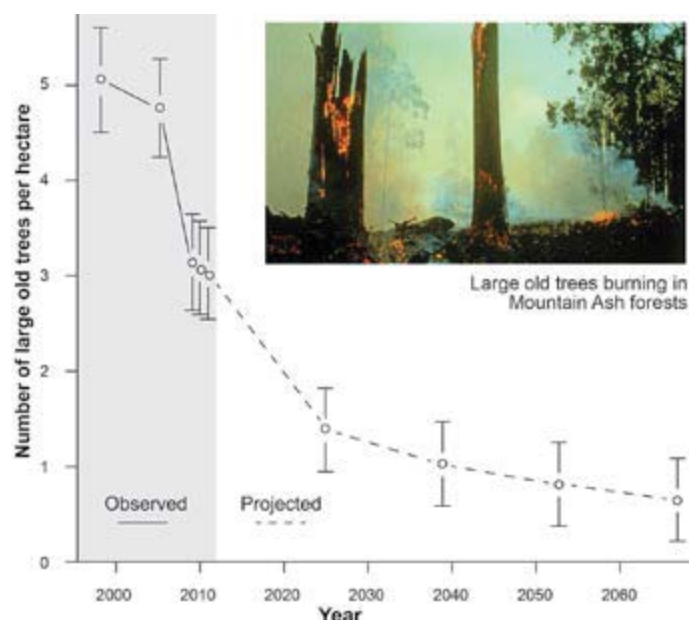


Figure 4. Projected changes in the numbers of large, old hollow-bearing trees in the Mountain Ash forests of the Central Highlands of Victoria. Projections are based on data in Lindenmayer *et al.* (2012a). Projections have been made to 2067, when stands dominated by regrowth dating from the 1939 wildfires (and which are currently the most widespread age cohort) first begin to develop cavities. Photo by D. Milledge.

et al. 2013). The extensive fires in 2009 damaged almost half of the known habitat of Leadbeater's Possum (S. Smith, Victorian Department of Primary Industries and Environment, personal communication 2013).

Although approximately 1/5th of the Mountain Ash forest of the Central Highlands of Victoria occurs in the closed water catchments and the existing Yarra Ranges National Park, viability analyses have indicated that this protected area, together with the existing set of prescriptions to manage Leadbeater's Possum (see Macfarlane *et al.* 1998), are insufficient to ensure the persistence of the species, especially in the advent of future wildfires (Lindenmayer and Possingham 1995). Moreover, in the medium to long term, forest dynamics mean that the location of areas of suitable habitat for Leadbeater's Possum can shift spatially. This, in turn, means that large areas of forest need to be protected to enhance the persistence of the species across landscapes (Lindenmayer and Possingham 1995).

Losses of old growth forest

Over the past century, the old growth estate in Mountain Ash forests has been substantially reduced in area and highly fragmented. Old growth forest is defined as a patch of forest exceeding 3 ha in size where the dominant overstorey trees are 120 years or older. Old growth Mountain Ash forests now cover 1886 ha (in 147 separate patches). This equates to 1.1% of the entire Mountain Ash forest estate (Figure 2; Lindenmayer *et al.* 2012a). The reduction and fragmentation of old growth forest is a result of more than a century of logging, and wildfires in 1926, 1932, 1939, 1983 and most recently 2009 (Lindenmayer *et al.* 2012a). Archival documents from the 1960s-1980s indicate that the Forest Commission of Victoria deliberately converted areas of old growth forest to stands of regrowth because the latter were considered to be more productive for wood supply.

Historical accounts (e.g. Houghton 1986), coupled with stand reconstruction work relating to tree age and stem diameters of large dead trees remaining within young stands (Lindenmayer and McCarthy 2002) identify that, prior to European settlement, at least 30% and possibly up to 60-80% of the Mountain Ash forest estate in the Central Highlands of Victoria was old growth (Lindenmayer 2009a).

Altered key ecosystem processes – changed fire regimes and impaired recruitment of large old trees

Key ecosystem processes have been disrupted in Mountain Ash forests. There appears to be an increased prevalence of large-scale, high severity wildfires in the past century (Lindenmayer *et al.* 2011a). This has direct negative effects on populations of Leadbeater's Possum (Lindenmayer *et al.* 2013), the amount of habitat for Leadbeater's Possum (S. Smith, Department of Primary Industries and Environment, personal communication 2013), and on populations of large old trees (Lindenmayer *et al.* 2012a). The increased prevalence of fire also has led to a marked reduction in the amount of old growth Mountain Ash forest (Lindenmayer *et al.* 2011a).

Logging is a key factor influencing fires in Mountain Ash forests (Lindenmayer *et al.* 2011a). Logging creates widespread dense, young regenerating stands that are at risk of repeatedly re-burning before they reach a more mature state. Lindenmayer *et al.* (2011a) have termed this feedback between wildfires and logging a “landscape trap” and it has made the disturbance dynamics of “trapped” Mountain Ash forest landscapes markedly different than those before European settlement. The landscape trap has the potential to create irreversible changes in disturbance dynamics and forest cover, resulting in a simplified and homogenised landscape pattern and vegetation structure (Lindenmayer *et al.* 2011a). Indeed, continued re-burning of Mountain Ash forest could ultimately eliminate this ecosystem altogether and see it replaced by an entirely different, frequent-fire adapted, vegetation type, such as stands dominated by *Acacia* spp. trees (Lindenmayer *et al.* 2011a). Moreover, modelling studies show that fires in rapid succession have the potential to eliminate populations of Leadbeater's Possum (Lindenmayer and Possingham 1995) and possibly other fire-sensitive species inhabiting Mountain Ash forests.

The recruitment, maturation and long-term persistence of large old trees is the second key ecosystem process that has been altered in Mountain Ash forests. As outlined above, rapid rates of decay and collapse of large old trees have been documented in Mountain Ash forests, with particularly pronounced rates of loss following wildfire. Clearfelling also rapidly accelerates the rate of loss of existing large old trees (Lindenmayer *et al.* 1990, 1997). It also precludes the recruitment of new trees because stems are cut down before they reach a sufficient age for the development of cavities (Lindenmayer 1994). Finally, the risk of re-burning of logged and densely stocked regenerating stands of Mountain Ash (Lindenmayer *et al.* 2011a) means that trees are killed before they reach an age where hollow development begins to occur. These three disruptive factors, individually or in combination, can have catastrophic consequences for the development and maintenance of old growth Mountain Ash forest.

Intersecting principles for forest restoration and forest biodiversity conservation

The overarching objectives of forest restoration in Mountain Ash forests are to: (1) conserve remaining populations of Leadbeater's Possum, (2) conserve existing residual elements of stand structure and natural forest cover by protecting remaining key structures, habitats, and patches, (3) restore those elements of forest biota and attributes of forest structure and forest cover that have been depleted, and (4) restore key ecosystem processes that lead to the maintenance of populations of species of conservation concern and assist in the creation of key elements of stand structure and appropriate patterns of landscape heterogeneity.

In each of the following sections, we outline a general conservation and restoration principle and then discuss the specific approaches needed to achieve these objectives for Mountain Ash forests. We summarise the principles and approaches in Table 1.

Table 1. Summary of forest biodiversity conservation and restoration principles and approaches for application in Victorian Mountain Ash forests

Biodiversity Principle	Conservation strategy	Restoration strategy
Conserve special species	Conserve existing locations of Leadbeater's Possum (Location records) (Protect all large old trees) (Appropriate buffer areas as logging exclusion zones)	Increase areas of suitable locations for special species like Leadbeater's Possum (Maintain buffering protocols for areas that are recruited for the species)
	Conserve existing areas of suitable habitat (Appropriate enhanced zoning) (Proper site-level surveys) (Buffers for suitable habitats) (Expand the streamside reserve system)	Increase areas of suitable habitat for special species like Leadbeater's Possum (Appropriate [enhanced] zoning) (Expanded buffers for suitable habitats) (Expand the streamside reserve system) (Increase the size of the old growth forest estate)
	Conserve all living and dead hollow-bearing trees (Appropriate buffers for hollow-bearing trees) (Expand the streamside reserve system) (Appropriate enhanced zoning)	Promote stand structural complexity across more of the forest estate (Restore the hollow tree recruitment process) (Appropriate [enhanced] zoning) (Expanded buffers for suitable habitats) (Expand the streamside reserve system) (Increase the size of the old growth forest estate)
Maintain patterns of landscape heterogeneity	Maintain existing landscape heterogeneity (Protect all remaining areas of old growth forest) (Expand the streamside reserve system) (Avoid logging intact areas and places where old growth forest has a high probability of developing)	Recreate suitable landscape heterogeneity (Appropriate zoning) (Expanded buffers for suitable habitats) (Expand the streamside reserve system) (Increase the size of the old growth forest estate)
	Maintain natural fire regimes Recommence the hollow tree recruitment process Avoid the loss of hollow-bearing trees	Restore impaired ecosystem processes (Restore appropriate fire regimes) (Restore the hollow tree recruitment process) (Increase the size of the old growth forest estate) (Expand the streamside reserve system) (Avoid logging intact areas and places where old growth forest has a high probability of developing)

Conserve existing important structures, habitats and other key areas

Protect known locations and special habitats for species of conservation concern

A key part of the conservation of any organism is to protect individuals (and hence the locations) where they are known to occur. This approach is particularly important for species that exhibit patterns of long-term site affinity (Caughley and Gunn 1996; Lindenmayer and Hunter 2010). Access to suitable habitat is also fundamental to the persistence of all organisms (Morrison *et al.* 2006) and

protection of existing areas of suitable habitat is therefore also a critical part of ensuring the persistence of species of conservation concern. Both approaches are necessary to be successful (Likens and Lindenmayer 2012). Buffers may be required to mitigate negative edge effects on retained habitat or known locations of populations (Kelly and Rotenberry 1993). The protection of these areas is also important as they can subsequently act as nodes around which to focus restoration efforts to expand the area of suitable habitat for target species.

Leadbeater's Possum is the species most in need of protection in Mountain Ash forests. Protection of locations where the species is known to occur is critical as: (1) the

species exhibits strong patterns of long-term site affinity – between 1997 and 2012 the probability of occurrence of Leadbeater's Possum on a site was significantly related to its prior occurrence on that site (Lindenmayer *et al.* unpublished data), and (2) animals from remaining populations may assist the recolonisation of previously burned areas (Lindenmayer *et al.* 2013). Colonies of Leadbeater's Possum are sensitive to the effects of logging in the surrounding landscape (Lindenmayer *et al.* 1993a). Locations known to have supported the species in the past 1-15 years need to be surrounded by a 1 km wide area of uncut forest. The size of the buffer is based on the known zone of negative influence of disturbed forest on the occurrence of the species (Lindenmayer *et al.* 1993a).

Leadbeater's Possum can be difficult to detect, and effective field surveys are labour intensive (Lindenmayer *et al.* 1991a). Thus, it is critical to protect areas of suitable habitat for the species, irrespective of whether the presence of animals has been confirmed in such areas. Because the probability of occurrence of the species at a site is significantly correlated with the number of hollow-bearing trees on a site (Figure 3), a forest zoning system has been established for protecting suitable habitat for Leadbeater's Possum (Macfarlane *et al.* 1998). However, the current zoning system is largely based on protecting living, hollow-bearing trees, but not dead ones. Yet dead trees are typically selected as nest sites by Leadbeater's Possum (Lindenmayer *et al.* 1991d) and they are most easily destroyed by logging operations. Information on the habitat requirements of Leadbeater's Possum, coupled with known data on nest tree selection by the species, identifies that the zoning system needs to be updated to be consistent with the known nesting requirements of the species and to ensure the protection of all 3-ha or larger patches of forest that support eight or more living and/or dead hollow-bearing trees.

Protect key elements of stand structural complexity – large old hollow-bearing trees

Structural complexity is a common feature of all natural forests throughout the world (Perry *et al.* 2008; Gustafsson *et al.* 2012) and a critical part of habitat suitability for many elements of biota in all forest ecosystems (Morrison *et al.* 2006). Structural complexity includes a wide variety of structural features of natural forest stands, such as trees from multiple age cohorts within a stand, large living and dead trees, large diameter logs on the forest floor, and vertical heterogeneity created by multiple or continuous canopy layers (Lindenmayer and Franklin 2002). The protection of key elements of stand structural complexity can be achieved in many ways. A common way of protecting those structures that are sensitive to the effects of human disturbances, such as logging operations and/or other kinds of edge effects, is to establish buffers (Kelly and Rotenberry 1993; Harper *et al.* 2005; Gustafsson *et al.* 2012). Effective buffer size can be determined using data on the processes affecting the elements of structural complexity (Laurance *et al.* 1997), and the environmental properties of the matrix surrounding key structures and patches (Ries *et al.* 2004).

Large old hollow-bearing trees are a critical element of stand structural complexity to be protected in Mountain Ash forests. The number of these trees is the key factor limiting populations of cavity-dependent animals in Mountain Ash forests, including Leadbeater's Possum (Lindenmayer *et al.* 2013). Because populations of large old hollow-bearing trees are declining rapidly, and it takes a prolonged period for new ones to develop (Lindenmayer *et al.* 2012b), it is essential to protect the remaining trees. Better protection of existing living and dead hollow-bearing trees means avoiding cutting them down or burning them within places broadly designated for logging, and also buffering existing trees within unlogged forest. We recommend unlogged forest buffers of 100 m in radius to protect existing hollow-bearing trees. The size of buffers is based on three key criteria: (1) empirical data which highlight the extent of destruction and/or collapse of hollow-bearing trees on logged and regenerated sites (Lindenmayer *et al.* 1990, 2012a), (2) empirical data on the spatial extent of collapse among hollow-bearing trees in strips of retained forest adjacent to logged areas (Lindenmayer *et al.* 1997), and (3) radio-tracking data on the spatial extent of animal movements by members of the same colony between multiple nesting sites in different hollow-bearing trees (Lindenmayer and Meggs 1996). In addition, the highest abundance of hollow-bearing trees occurs in gullies (Lindenmayer *et al.* 1991b), so increasing the width of riparian (streamside) reserves from 40 m to 100 m will better protect trees in those parts of landscapes most likely to escape high-intensity fire, allowing them to develop to a hollow-bearing age.

Maintain existing important patches that contribute to landscape heterogeneity

Landscape heterogeneity is another feature common to all natural forests (Bormann and Likens 1979; Burton *et al.* 2003; Perry *et al.* 2008) and it encompasses the diversity, size, and spatial arrangement of patches of different kinds of vegetation, within-vegetation type-variation (e.g. age cohorts of a given forest type) and habitat for particular elements of the biota (Spies and Turner 1999; Bennett *et al.* 2006). The maintenance of landscape heterogeneity is an essential principle for conserving forest biodiversity (Lindenmayer and Franklin 2002; Allouche *et al.* 2012). The diversity, size, and spatial arrangement of habitat patches are important for forest biota in the vast majority of forest types worldwide (e.g. Turner *et al.* 1997; Galetti *et al.* 2013), including a number of species in Mountain Ash forests (e.g. see Lindenmayer *et al.* 1999a, 2013).

The amount and spatial cover of old growth forest are critical components of landscape heterogeneity in Mountain Ash forests. Given the highly fragmented and relictual current levels of cover, it is critical to protect all remaining patches of old growth. These patches also need to be protected by buffers, because logging in surrounding areas can increase the risk of collapse of the large old trees within fragmented, old growth patches (Lindenmayer *et al.* 1997).

Restore and expand populations of key species, key structures, restore patterns of old growth landscape cover, and restore key ecosystem processes

Although an important general principle for forest restoration is to maintain populations of target species, key structures, and habitats, this alone can be insufficient in forests that have been extensively modified and degraded by human disturbance. A second principle then becomes critical; that is, to proactively restore those elements of forest biota and attributes of forest structure and forest cover that have been depleted. These activities include: (1) halting the decline of threatened species and then re-building populations so they are viable in the long term, (2) increasing the area of critical habitat, including the expansion of key elements of stand structure that can influence localised habitat suitability, (3) restoring patterns of landscape heterogeneity, and (4) restoring key ecosystem processes.

Expand populations of key species, and increase the area of suitable habitat

The current state of Mountain Ash forest, coupled with viability analyses, has highlighted the strong risk of extinction of Leadbeater's Possum in the coming 20-30 years without forest restoration and especially in the advent of additional wildfire in that time (Lindenmayer and Possingham 1995). We suggest that there will be substantial increases in the viability of Leadbeater's Possum if the protection of existing hollow-bearing trees, areas of key habitats and existing stands of old growth forest is coupled with major efforts to significantly increase populations of large old trees, expand areas of suitable habitat, and expand the cover of old growth forest. Restoration programs in Mountain Ash forests must therefore increase population size and the spatial coverage of large old hollow-bearing trees – although this will take at least 50 years to begin to take effect (Lindenmayer *et al.* 2012a). Such restoration will lead to more suitable habitat for Leadbeater's Possum. An expanded network of riparian reserves also will assist this process, in particular because such places are where large old trees are more likely to occur (Lindenmayer *et al.* 1991b). Another strategy to promote the recruitment of new cohorts of large old trees, and new areas of additional habitat, will be to dispense with clearfelling and replace it with more environmentally-sensitive retention harvesting practices (*sensu* Gustafsson *et al.* 2012). Experimental work has shown that variable retention harvesting is logistically feasible in Victorian Mountain Ash forests (Lindenmayer *et al.* 2010b).

Restore patterns of landscape heterogeneity

Many highly degraded forest landscapes are characterised by landscape homogeneity with corresponding negative implications for forest biodiversity and key ecosystem processes (see below) (Covington 2003). A critical part of forest restoration must be to restore landscape heterogeneity. Human and natural disturbances (as well as feedbacks between them; e.g. see Cochrane and Laurance

2008) are significant drivers of landscape homogeneity, and hence restoration efforts must deal effectively with these drivers (Noss *et al.* 2006). Restoring patterns of landscape heterogeneity will sometimes require determining what are appropriate “natural” patterns (e.g. in the absence of extensive recent human disturbance regimes like logging operations) and then setting targets for desired levels and spatial patterns of cover of particular types of patches (Forman 1995; Stankey *et al.* 2003).

Restoring patterns of landscape heterogeneity in Mountain Ash forests will require an extensive expansion of the current relictual and highly fragmented old growth estate. We argue that the best way to do this will entail setting a management target for an area corresponding to the minimum area of 30% old growth/multi-aged forest that reconstruction analyses by McCarthy and Lindenmayer (1998) found were likely to have characterised Mountain Ash forests prior to European settlement. To ensure that the old growth estate is well distributed, we recommend that an aim should be to ensure that, at any given time, 30% of the area of each 3000-6000 ha forest management unit within areas broadly designated for wood production will be grown through to an old growth stage. Notably, a target of 30% old growth over the long term will require significantly more than 30% of the forest to be reserved, because of the risk of areas being burned in the 120+ years that it takes for forest to reach an old growth stage. Areas targeted for old growth recruitment should be located on comparatively flat topography and on sheltered aspects that are characterised by low levels of incoming radiation. Such places have reduced susceptibility to high frequency and high severity wildfire (Lindenmayer *et al.* 1999b; Mackey *et al.* 2002).

The creation of additional areas of old growth forest has a number of important additional ecological benefits. First, a greater area of old growth may help circumvent the landscape trap problem by altering the patterns of fire-proneness in landscapes dominated by young stands of dense regrowth forest. Second, fires that do occur in stands of old growth forest would be more likely to either result in multi-aged forest (McCarthy and Lindenmayer 1998) and/or create a pulse of large old dead hollow-bearing trees (Lindenmayer *et al.* 1991b), thereby subsequently leading to the development of suitable habitat for cavity-dependent animals, like Leadbeater's Possum. Third, a significantly expanded area of old growth increases the chance that, even in the advent of a large fire in the future, at least some areas will remain unburned and therefore act as refugia within which populations of both large old trees and Leadbeater's Possum will persist.

Restore key ecosystem processes

The success of all conservation and restoration programs ultimately depends on effectively tackling the underlying altered ecosystem processes that threaten a given ecosystem or species in that ecosystem (Caughley and Gunn 1996). Two key ecosystem processes which have been disrupted in Mountain Ash forests are fire and the recruitment of large old hollow-bearing trees. Both processes interact (Lindenmayer *et al.* 2011a) (see Figure 6) and directly and indirectly influence the occurrence

and viability of populations of Leadbeater's Possum (Lindenmayer and Possingham 1995), habitat suitability for Leadbeater's Possum (Lindenmayer 2009a), and the structure and composition of forest stands and landscapes (Lindenmayer 2009b).

Restoration of natural fire regimes in Mountain Ash forests must prevent the further development of landscape traps by expanding the amount of old growth cover. To achieve this goal, the amount of logging *must* be reduced significantly, particularly in areas which would otherwise have had comparatively low levels of fire proneness and hence would have been more likely to support old growth and/or multi-aged forests (see Mackey *et al.* 2002). Therefore, wood production will need to be excluded from large areas of presently intact (unburned) forest to ensure they are not made more fire prone.

Restoration of the large old tree recruitment process requires four actions: (1) protecting all existing large old trees, (2) protecting existing areas of forest where such trees might not presently occur but which have a high probability of supporting trees in the future (e.g. riparian areas and sheltered parts of landscapes (Lindenmayer *et al.* 1991b, 1999b), (3) dispensing with current clearfell logging practices that accelerate the loss and collapse of large, old hollow-bearing trees and prevent their recruitment (Lindenmayer *et al.* 1990, 1997), and (4) reducing the frequency and severity of fire that can kill and/or consume hollow-bearing trees – as we outlined above. These actions underscore the importance of a continuum of restoration approaches; from individual trees to critical parts of landscapes, as well as species-based, and ecosystem process-based, strategies.

The restoration of key ecosystem processes, such as fire and the recruitment of large old hollow-bearing trees in Mountain Ash forests also will have significant positive effects on other important ecosystem processes. These include levels of nutrient cycling and, in particular, the extent of carbon storage in Mountain Ash forests. This is because large old trees and old growth forests are extremely carbon-dense (Keith *et al.* 2009) and store significantly more carbon than areas of young forest, particularly those that have been logged (Keith *et al.* 2013). In addition, the protection and spatial expansion of large old trees and the restoration of natural fire regimes in Mountain Ash forests will have profound positive impacts on the production of water. Catchments dominated by large old trees and old growth forests yield significantly more water and higher quality water than catchments comprised primarily of young forest (Vertessey and Watson 2001; Viggers *et al.* 2013).

Mapping the spatial location of forest restoration strategies

The forest restoration and forest biodiversity conservation principles and practices we have outlined for Mountain Ash forests will demand careful mapping of logging exclusion areas (e.g. see Figure 5). Such mapping would delineate: (1) known location records of Leadbeater's Possum and the 1 km buffers around these locations, (2) the location of special habitats, particularly areas of

suitable habitat for Leadbeater's Possum, (3) the location of individual living and dead hollow-bearing trees and the 100 m buffers to protect them, (4) the network of widened streamside reserves, and (5) areas to be excluded from logging to rebuild the old growth forest estate. This mapping must be accompanied by rigorous, on-the-ground surveys to properly assess all proposed logging blocks and identify harvest exclusion areas. Such mapping also would need to be dynamic and updated regularly in response to changing conditions.

The need for an expanded large ecological reserve

Large ecological reserves are at the core of any credible forest biodiversity conservation plan (Lindenmayer and Franklin 2002). This is particularly true in the case of Victorian Mountain Ash forests. Indeed, there are several key reasons why an expanded large ecological reserve is needed in Mountain Ash forests, in addition to forest restoration strategies within areas broadly designated for pulp and timber production. First, viability analyses have indicated that the current formal reserve is too small to support viable populations of Leadbeater's Possum, particularly if additional fires occur in the next 50-100 years. Second, a large ecological reserve is an area where there is a reduced number of stressors and, in turn, where there is a greater chance that natural fire regimes and the processes of recruitment of large old trees can be restored.

We argue that an expanded National Park must be located where: (1) It connects key areas of habitat for Leadbeater's Possum and also connects existing reserves. Such enhanced connectivity would promote the dispersal of the species throughout forest landscapes, including those regenerating after wildfire. (2) It encompasses areas of suitable habitat, existing areas of old growth forest and areas where previous environmental modelling (Mackey *et al.* 2002) has indicated that mixed aged forest (Lindenmayer *et al.* 1999b) and old growth is most likely to develop. Furthermore, the reserve must cover sufficient area to be larger than the size of major disturbance events such as wildfires (Baker 1995). There also must be sufficient habitat remaining to support viable populations of Leadbeater's Possum, even if a major conflagration occurs (Lindenmayer and Possingham 1995). Current management practices within the Yarra Ranges National Park are consistent with the conservation objectives for Leadbeater's Possum as major threatening processes such as clearfell logging and post-fire salvage logging are excluded from this important protected area.

Prioritising actions

We have outlined conservation and restoration actions for managing the existing Mountain Ash forest estate. All of these actions are important, but do some have priority over others? We suggest that given the current parlous state of populations of Leadbeater's Possum (see Lindenmayer *et al.* 2013), all known colonies, and areas of currently suitable habitat, including individual large old hollow-bearing trees, must be protected with appropriate buffers of surrounding unlogged forest. A second priority



Figure 5. A section of the 6600 ha Ada Forest Block highlighting the spatial locations of the different, on-ground forest restoration strategies in Mountain Ash forest. The image shows buffers around large old living and dead trees, streams, relictual stands of old growth forest and known records of Leadbeater’s Possum.

must be to establish an expanded National Park where logging is removed as this major threatening process is degrading the Mountain Ash ecosystem and threatening the persistence of Leadbeater's Possum. The boundaries of such an expanded formal reserve would aim to include as many areas of suitable habitat and known locations of the species as possible. The third key restoration action must be to expand the area of old growth forest. Both the second and third priorities would aim to restore not only patterns of landscape heterogeneity, but also the key ecosystem processes of fire and large old tree recruitment. The current severe impairment of these key processes in Mountain Ash forests, if not addressed, threatens not only the persistence of Leadbeater's Possum, but also the persistence of the forest ecosystem itself (Lindenmayer *et al.* 2011a). Restoration of ecological processes and patterns of landscape heterogeneity are large-scale and long-term objectives but, if successful, will help achieve effective conservation outcomes for the protection of Leadbeater's Possum and its habitat at smaller scales.

maintaining patterns of landscape heterogeneity, and perpetuating key ecosystem processes. Thus, the principles for forest restoration and forest biodiversity conservation are distinctly multi-faceted and multi-scaled. This is because they: (1) encompass species-level approaches through to ecosystem-level approaches, and (2) address problems with spatial patterns of forest cover as well as disrupted ecological processes (Likens and Lindenmayer 2012). The principles for forest restoration and forest biodiversity conservation also span multiple temporal scales by encompassing strategies that protect current individual animals, trees and habitats, promote the medium term recruitment of trees and habitats (e.g. over the next 70-150 years), and aim to create and perpetuate long-term landscape heterogeneity by rebuilding the cover of old growth forest (150 years+).

General discussion

General principles for forest restoration are to keep the key residual elements of original natural forest cover (e.g. remaining populations of target species, key structures, habitats, and patches) and to restore those elements of forest biota, and attributes of forest structure and forest cover that have been depleted (e.g. Lamb 2011). Using a case study of Australian Mountain Ash forests, we have shown how these two broad principles intersect strongly with general principles for forest biodiversity conservation developed by Lindenmayer and Franklin (2002) – in particular conservation principles associated with conserving populations of special species and their habitats, maintaining stand structural complexity,

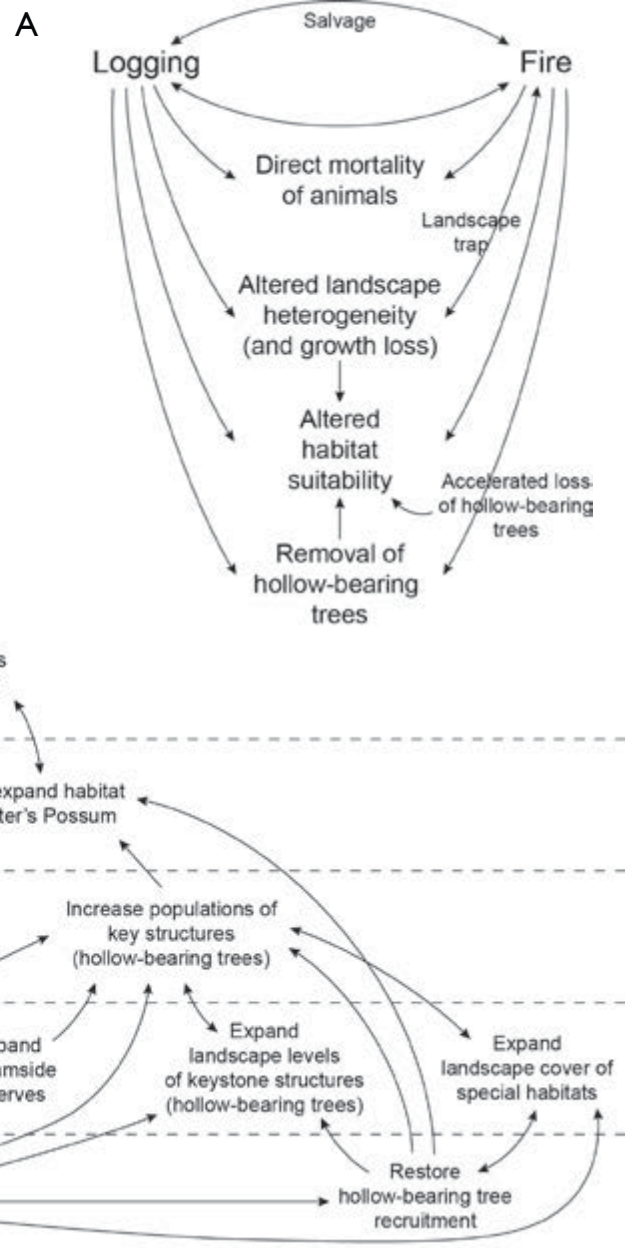


Figure 6. Conceptual diagrams of: (A) interacting processes which are degrading Mountain Ash forests and threatening forest biodiversity, and (B) the intersection of forest restoration and forest biodiversity conservation principles aimed at the restoration of Mountain Ash forests.

Interactions between principles for forest biodiversity conservation and forest restoration

While we have treated the various restoration and conservation principles separately throughout this paper, and in our case study, we are acutely aware that they can interact at different spatial scales and over time (see Figure 6). Indeed, our case study on the intersection between forest restoration principles and general principles for forest biodiversity conservation has highlighted the critical inter-relationships between key ecological processes and spatial patterns of species distribution, key structures and vegetation cover. For example, efforts to restore landscape heterogeneity by restoring the spatial extent of the old growth forest estate will assist in the restoration of fire regimes (Lindenmayer *et al.* 2011a) and the restoration of the recruitment of large trees (Lindenmayer *et al.* 2012a). Efforts to restore landscape heterogeneity also will increase the abundance and spatial distribution of populations of large old trees and expand the area of suitable habitat for cavity-dependent species like Leadbeater's Possum. Similarly, the establishment of expanded riparian buffers will contribute to both the protection of large old hollow-bearing trees (Lindenmayer *et al.* 1991b) as well as the restoration of patterns of landscape heterogeneity (as fire is less likely to occur or to burn at high severity in these areas, leading to the development of old growth stands; see Mackey *et al.* 2002). The protection of all existing individual, large old hollow-bearing trees (and their associated 100 m buffers) will contribute to landscape-level coverage of these key elements of stand structural complexity. Therefore, restoration and conservation efforts at one scale have considerable potential to create benefits at other (smaller or larger) scales. The potential for positive interactions between forest biodiversity and forest restoration principles is an important antidote to the interacting negative processes that drive the degradation of not only Mountain Ash forests (see Figure 6), but also of many other forest ecosystems worldwide (Lindenmayer *et al.* 2011a). Successful implementation of these processes will be critical to prevent the extirpation of the endangered Leadbeater's Possum, among other hollow-dependent species in this ecosystem.

Tackling the underlying drivers of current forest conditions

The amount and type of past and present (clearfell) logging is one of the key drivers underlying the current condition of Mountain Ash forests and the parlous state of remaining populations of large old hollow-bearing trees and populations of Leadbeater's Possum. Past logging (including post-fire, salvage logging) is a major threatening process because it has: (1) converted large areas of old growth forest to young stands of regrowth forest and thereby radically altered patterns of landscape heterogeneity, (2) created extensive stands of structurally-simplified, regrowth forest leading to the loss of much suitable habitat for Leadbeater's Possum, (3) promoted

the rate of collapse of large old hollow-bearing trees, (4) severely impaired the recruitment of new populations of old hollow-bearing trees, and (5) interacted with natural disturbances to alter the fire regime and create a landscape trap which, in turn, has further accelerated the loss of old-growth forest, large old trees and patches of habitat for individual populations of Leadbeater's Possum.

The long-term success of forest restoration, and attempts to conserve forest biodiversity, will therefore require remediation of the ecological problems created by logging. The strategies for establishing new buffers for protecting individual trees, key habitats and remnant patches of old growth forest, coupled with recommendations to expand significantly the area of old growth beyond current relictual levels, will mean a substantial reduction in the area available for logging, and hence reduced estimates of the sustained yield of pulpwood and sawlogs from Mountain Ash forests. However, such reductions are essential to create sufficient 'environmental margin' to not only maintain, but also significantly improve, other key forest values and, in turn, establish forest management regimes that are truly ecologically sustainable.

The two other drivers of the present, degraded condition of the Mountain Ash forest are fire and the lack of recruitment of large old hollow-bearing trees. A reduced amount of logging coupled with a change to the current harvesting practice of clearfelling will also make a significant contribution to rectifying the negative effects of both these drivers.

Additional information needs

Despite extensive research over the past three decades, key knowledge gaps remain that need to be filled to guide best practice forest restoration and forest biodiversity conservation in the Mountain Ash forests of the Central Highlands of Victoria. Such knowledge gaps are also a key reason to protect known locations of Leadbeater's Possum and known habitat for the species as efforts to recreate "natural" habitats and spatial patterns of suitable habitat will be done with incomplete ecological knowledge. We do not present an exhaustive "shopping list" of management research needs here, but point out that one outstanding area of additional research is work on how to accelerate the rate of development of cavities in trees. Work on stimulating cavity development is well developed in North America (e.g. Bull *et al.* 1981; Bull and Partridge 1986) but there is no equivalent body of work in Australian forest ecosystems. This new research is needed in Mountain Ash forest because traditional methods of providing artificial cavities through nest boxes have been unsuccessful (Lindenmayer *et al.* 2003, 2009).

A second area of further work must be to determine how much forest needs to be reserved to achieve and maintain a level of 30% cover of old growth forest in perpetuity. The impacts of fire mean that some areas set aside to grow through to an old growth stage will be burned before they can attain ecological maturity. This eventuality may mean that, for example, 60% of a forest block will have to be set aside to achieve the

objective of reaching and then maintaining a level of 30% cover of old growth. However, the actual amount of forest required to be protected (with associated levels of uncertainty) needs to be determined quantitatively, particularly as this proportion can be expected to increase with further alterations to fire regimes as a result of climate change.

Finally, we argue that it is important to maintain existing, long-term work that has been underway in the Central Highlands of Victoria for the past 30 years. Long-term, adaptive monitoring is critical for underpinning informed forest and biodiversity conservation and management – as highlighted by the use of detailed ecological science in this paper to underpin the development of principles for forest biodiversity conservation and forest restoration.

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The management of Leadbeater's Possum and the Mountain Ash forests within which it is virtually confined has been highly contested for more than four decades. The ideas and concepts presented in this

Concluding remarks

Our focus in this paper has been on the conservation and restoration of Leadbeater's Possum and Mountain Ash forest in the Central Highlands of Victoria. The specific prescriptions we have outlined for conservation and restoration have been tailored for this particular species and the Mountain Ash ecosystem. However, these prescriptions are drawn from general principles for forest biodiversity conservation (see Lindenmayer and Franklin 2002) and general principles for forest restoration (Hobbs *et al.* 2012). These general principles will be relevant to virtually all forest ecosystems, although how they translate to specific prescriptions to guide particular management action will vary with the ecosystem (and the biodiversity within that ecosystem) that is targeted for management.

paper have been debated and discussed with many people over three of those decades. Claire Shepherd assisted with many editorial aspects of manuscript preparation.

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APPENDIX I



A stand of Mountain Ash forest that was burned in the 2009 wildfires. Photo, D. Blair.



Clearfelled Mountain Ash forest. Photo, D. Lindenmayer.

APPENDIX I



(a) Leadbeater's Possum, and
(b) a hollow-bearing tree used
by Leadbeater's Possum.

Photos, D. Lindenmayer and
D. Blair.



APPENDIX I



Stand of old growth forest prior to the 2009 wildfires. Photo, E. Beaton.



Accelerated tree fall within a retained linear strip between two clearfelled coupes. Photo, D. Lindenmayer.