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Integrating forest biodiversity conservation and restoration ecology principles to recover natural forest ecosystems

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Abstract Effective conservation of forest biodiversity and effective forest restoration are two of the biggest challenges facing forest managers globally. I present four general principles to guide strategies aimed at meeting these challenges: (1) protect and restore populations of key species and their habitats, (2) conserve and restore key attributes of stand structural complexity, (3) maintain and restore natural patterns of landscape heterogeneity, and (4) maintain and restore key ecological processes. The complexity associated with these principles is that how they will be practically implemented on the ground will invariably be ecosystem specific as what constitutes stand structural complexity or landscape heterogeneity will vary between ecosystems. Here I demonstrate the practical application of the four general principles in a detailed case study of conservation and restoration in the Mountain Ash (*Eucalyptus regnans*) forests of the Central Highlands of Victoria, south-eastern Australia. These forests are characterized by declining species, loss of key elements of stand structural, loss of old growth forest, altered patterns of landscape heterogeneity, and altered ecosystem processes. I highlight how altered management practices in Mountain Ash forests that are guided by our four general principles can help conserve existing biodiversity and underpin effective forest restoration. Consideration of our general principles also can identify policy deficiencies that need to be addressed to enhance restoration and biodiversity conservation.

Keywords Forest biodiversity conservation · Restoration ecology · Landscape heterogeneity · Biodiversity

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Introduction

Significant losses of forest biodiversity (Gibson et al. 2011; Tilman et al. 2017) and, conversely, the need for restoration of millions of hectares of degraded forest (Crouzeilles et al. 2016; Menz et al. 2013) are two of the greatest issues challenging forest managers globally. In an attempt to meet these challenges, there are some general principles that can help guide the conservation of forest biodiversity and the restoration of forest ecosystems (and their associated biota) (Lamb 2011; Lindenmayer and Franklin 2002). First, is the need to protect and restore populations of key species and their habitats. These species may include not only those of conservation concern but also taxa that play critical roles in key ecosystem processes such as seed dispersal, pollination and nutrient cycling. Second, is the need to conserve and restore key attributes of stand structural complexity. Stand structural complexity is defined as the presence and spatial arrangement of stand characteristics (Lindenmayer and Franklin 2002). Important attributes of forest stands can include large old trees, understorey plants, and structures like mistletoe and moss-mats. Third, is the need to maintain and restore natural patterns of landscape heterogeneity. Landscape heteroegeneity is defined as the diversity, size and spatial arrangement of habitat patches in a forest landscape (Lindenmayer and Franklin 2002). Fourth is the need to maintain and restore key ecological processes that influence forest ecosystems including natural disturbance regimes, pollination, seed dispersal, and the recruitment of tree and other plant species.

These principles, as well as others like the maintenance and restoration of connectivity and the maintenance and restoration of aquatic ecosystems (see Lindenmayer and Franklin 2002), can be useful to guide both the conservation of existing forest biodiversity and forest ecosystems and restore biodiversity that has declined and ecosystems that have been depleted or degraded. How these conservation and restoration principles are implemented on the ground will invariably be ecosystem specific as, for example, what constitutes appropriate stand structural complexity and landscape heterogeneity (and how they are shaped by key ecological processes), will vary between different forest ecosystems. On this basis, the most appropriate way to demonstrate the practical application of these general principles is through a case study (see Hall and Fleischman 2010). In this paper, I present a detailed case study of the application of biodiversity conservation and restoration principles in the Mountain Ash (*Eucalyptus regnans*) forests of the Central Highlands of Victoria, south-eastern Australia. These forests are a useful case study for three reasons. First, they have been subject to extensive research for the past 34 years (Lindenmayer 2009; Lindenmayer et al. 2015a) with the associated studies providing empirical support for application of general principles. Second, the Mountain Ash ecosystem is characterized by an array of problems such as declining populations of species, widespread loss of key elements of stand structure, altered landscape heterogeneity, and key ecosystem processes. Indeed, the Mountain Ash ecosystem is classified as Critically Endangered under IUCN Red List Ecosystem criteria (Burns et al. 2015) and has a very high probability of collapse in the coming 30–50 years (Lindenmayer et al. 2016b). Hence, the general principles outlined in this paper are highly relevant to addressing and reversing these problems. Third, many of the conservation and restoration challenges facing the Mountain Ash ecosystem are replicated in many other ecosystems globally (Lindenmayer et al. 2016b; Messier et al. 2013) such as the boreal forests of the Northern Hemisphere (Bradshaw et al. 2009; Burton et al. 2003) and the wet conifer forests of the Pacific Northwest of the USA (Franklin et al. 2002;

Haynes et al. 2006). Therefore, the general principles outlined in this paper have broad utility for application in other forests, although the specifics of their application will vary between ecosystems.

In this paper, I first briefly outline some of the key conservation, restoration and management challenges in the Mountain Ash forests of the Central Highlands of Victoria. I then describe how general conservation and restoration principles can be used to guide specific conservation and restoration strategies and on-the-ground practices to address underlying ecological problems in Mountain Ash forests. I conclude with some general commentary about the management and policy implications of enhanced and integrated conservation and restoration strategies.

Background—the Mountain Ash forests Of Victoria

The Mountain Ash forests of the Central Highlands of Victoria occur in a 60 km × 80 km area, approximately 1–2 h north-east of Melbourne in the state of Victoria, south-eastern Australia (Fig. 1). They are dominated by Mountain Ash (*Eucalyptus regnans*) trees which are the tallest flowering plants on earth with individual stems reaching approximately 100 m in height (Lindenmayer et al. 2016b).

There is approximately 157,000 ha of Mountain Ash forest in the Central Highlands of Victoria (Keith et al. 2017b). The primary form of natural disturbance in these forests is infrequent, high-severity wildfire (McCarthy et al. 1999; Lindenmayer et al. 2011), with the last major conflagration occurring in 2009 when 78,300 ha of the forest estate was

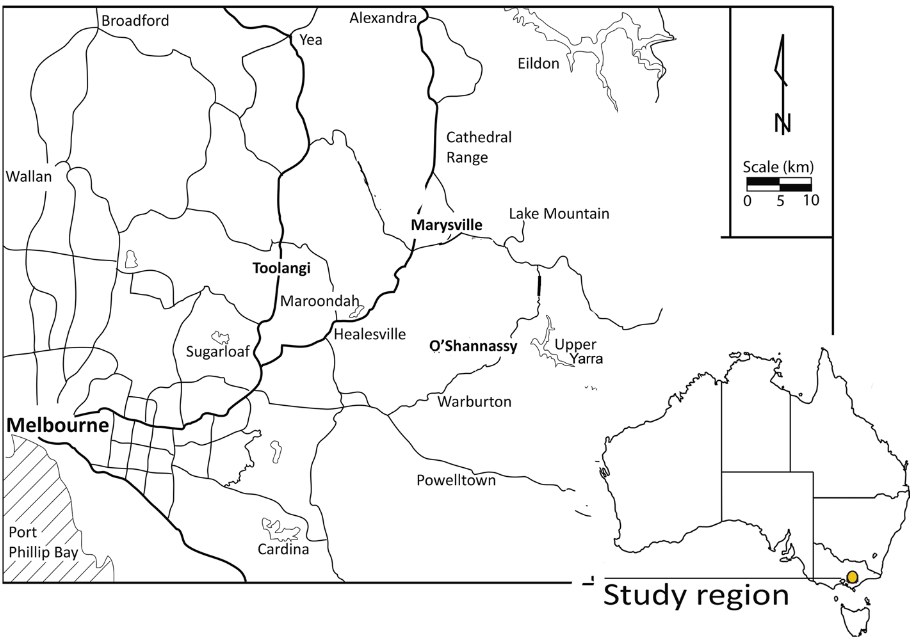

Fig. 1 Broad location of the Central Highlands of Victoria

burned (Keith et al. 2017b). The primary form of human disturbance in Mountain Ash forest is clearcut logging which is permitted in the ~80% of the forest estate broadly designated for timber and pulpwood production, although codes of practice exclude timber harvesting from parts of that area (Flint and Fagg 2007). The predominant silvicultural system is conventional clearcutting in which all merchantable trees are removed from cutblocks of 15–40 ha in size. Up to three contiguous cutblocks can be harvested in a given year over a 3 year period (Fig. 2).

Mountain Ash forests have a range of ecological and economic values. They provide almost all of the water for the 4.5+ million inhabitants of the city of Melbourne (Viggers et al. 2013), store large amounts of carbon (Keith et al. 2009), support habitat for many native taxa, including several of conservation concern such as the Critically Endangered Leadbeater's Possum (*Gymnobelidues leadbeateri*) and the vulnerable Greater Glider (*Petauroides volans*) (Lindenmayer et al. 2015a). Mountain Ash forests are used extensively by the tourism and recreation industries (Keith et al. 2017b) and are also a source of substantial quantities of pulpwood for the manufacturing of paper (Keith et al. 2014).

There are significant ecological and environmental problems in Mountain Ash forests. Populations of conservation-listed species are declining significantly (Keith et al. 2017a). Populations of large old trees, which are key nesting sites for almost all species of arboreal marsupials (including Leadbeater's Possum and the Greater Glider) are also in significant decline. Within 30 years, populations of such trees are predicted to reach levels

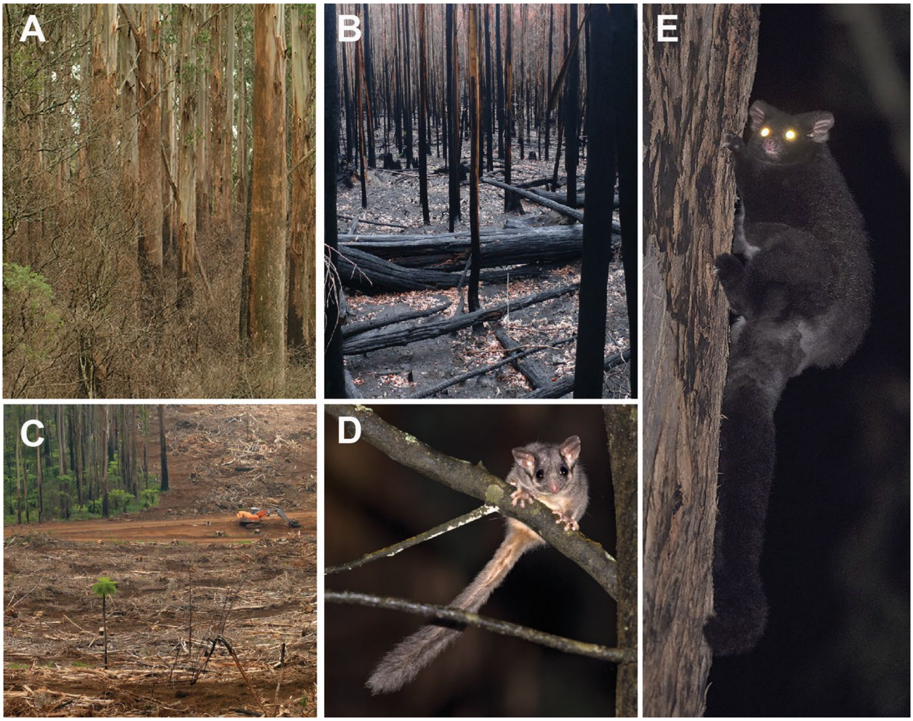

Fig. 2 Photo series from the Mountain Ash forests of the Central Highlands of Victoria. **a** Stand of old growth forest. **b** Cutblock harvested by clearcutting. **c** A stand of forest burned in the 2009 wildfires (Images by Dave Blair). **d** Leadbeater's Possum. **e** Greater Glider (Images by Tim Bawden)

95% lower than they were in 1997 (Lindenmayer et al. 2016a). The amount of old growth Mountain Ash forest is at historically low levels, approximately 1% of the forest estate is old growth, down from 30 to 60% at the time of white settlement of Australia (Lindenmayer et al. 2015a). The old growth estate of 1886 ha is highly fragmented and dispersed across 147 patches (Lindenmayer et al. 2015a). Thus, there has been a fundamental shift in patterns of landscape heterogeneity in Mountain Ash forests, with formerly large areas of old forest being replaced by extensive younger regrowth forest that now surround spatially limited patches of old growth forest. Finally, some ecosystem processes in Mountain Ash forest have been substantially altered. First, widespread clearcutting has impaired both the process of recruitment of large old trees and accelerated the rate of loss of existing large old trees (Lindenmayer et al. 2012). Second, the historical mean fire interval in the Mountain Ash ecosystem has been estimated to be approximately 75–120 years (McCarthy et al. 1999), but there has been five major wildfires in the past century, suggesting an increase in fire frequency (which is a fundamental component of the fire regime in this system). In addition, extensive areas of logged and subsequently regenerated forest now burn at significantly higher severity than intact forest (Taylor et al. 2014).

The ecological problems in Mountain Ash forests are intimately inter-related (Fig. 3). For example, old growth forest is where the abundance of large old trees is highest (Lindenmayer et al. 2000) and the rarity of old growth forest is in turn contributing to the rarity of large old trees across the Mountain Ash forest estate (Lindenmayer et al. 2016a). Large

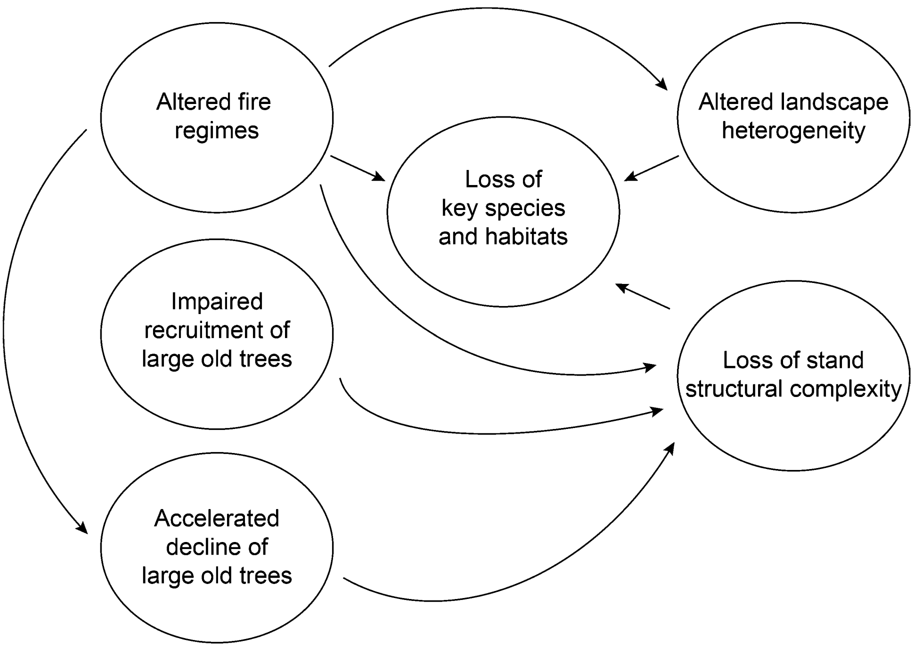

Fig. 3 Interaction of drivers of decline or change in key species, stand structural complexity, landscape heterogeneity, and key ecosystem processes in the Mountain Ash forests of the Central Highlands of Victoria, south-eastern Australia. Wildfire, clearcut logging and interactions between these forms of natural and human disturbance are key factors underpinning the drivers of decline in the Mountain Ash forests (see text)

old trees are the primary nesting and denning habitat for cavity-dependent arboreal marsupials (Lindenmayer et al. 2017a) and the paucity of these trees is a major contributing factor to the species declines in Mountain Ash forests (Keith et al. 2017a). In addition, altered ecological processes such as recurrent high-severity wildfire is contributing to the loss of old growth forest (Lindenmayer et al. 2015a), the loss of large old trees (Lindenmayer et al. 2012), and the decline in populations of species (which are often absent from burned areas Lindenmayer et al. 2013).

Conserving biodiversity and restoring Mountain Ash forests

The current status of the Mountain Ash forest estate, as well as the status of key elements of the biota within the ecosystem, indicate an urgent need to both strengthen conservation practices and adopt forest restoration strategies in ways closely aligned to the general principles articulated at the outset of this paper. In the following section, I outline some required conservation and restoration strategies.

Protect and restore populations of key species and their habitats

Over the past 10–20 years there has been a substantial increase in the number of threatened and endangered animal and plant species within Mountain Ash forests (Keith et al. 2017a). Two species of conservation concern undergoing significant population declines are Leadbeater's Possum and the Greater Glider. These are largely sedentary species of arboreal marsupials with high levels of long-term site affinity and are also sensitive to the effects of clearcut logging (Lindenmayer et al. 2015a). On this basis, known locations where these species have been recorded need to be exempt from timber harvesting. In addition, location records of the species should be buffered by stands of unlogged forest. The optimal size of buffers of unlogged forest around known location records of these species remain unclear. However, I suggest that, based on movement patterns of the species (Lindenmayer et al. 2004, 2017b), appropriate buffers of at least 200 m in radius are required around known locations of Leadbeater's Possum and the Greater Glider.

Beyond the need for immediate protection of existing location records of animals, there is also a need to quantify what constitutes a viable population of a given species of conservation concern. This has recently been done for both Leadbeater's Possum and the Greater Glider, with Population Viability Analyses suggesting that large parts of the Mountain Ash forest estate need to be formally protected as permanent logging exclusion areas to ensure a high probability of the persistence of these species over the next 50 years (Taylor et al. 2017; Todd et al. 2016).

Conserve and restore key attributes of stand structural complexity

Large old hollow-bearing trees are a critical component of stand structural complexity in Mountain Ash forests. The trees occupied by arboreal marsupials of conservation concern are typically 190 or more years old (Lindenmayer et al. 2017a). The increasing rarity of these trees and the prolonged period (> 120 years) before the natural recruitment of new cohorts of such trees (Lindenmayer et al. 2012) means it is critical to protect all existing old hollow-bearing trees. Although hollow-bearing trees are not cut down during logging operations, they are often badly damaged and collapse soon after. This leads to them being uncommon in harvested and regenerated stands (Lindenmayer et al. 2016a). Enhanced protection of these trees will require them to be buffered by areas of intact (unlogged) forest. The optimal size of such buffers remains unknown. However, recent work has found the probability of tree collapse increases significantly with the amount of cutover forest in the surrounding landscape at a distance of up to 2 km (Lindenmayer et al. unpublished data). I suggest that unlogged buffers of at least several 100 m around existing large old hollow-bearing trees need to be established, particularly around places where there are high concentrations of such trees. Notably, other studies have highlighted where large old hollow-bearing trees are most abundant (Lindenmayer et al. 2016a), making it possible to target those parts of Mountain Ash landscapes most appropriate for buffer establishment. Importantly, the strategy of establishing buffers of unlogged forest not only increases the protection of existing large old hollow-bearing trees but also increases the chances of recruitment of new cohorts of trees that can replace old trees when they are lost.

An additional way to promote the restoration of stand structural complexity is to replace conventional clearcut logging with other more environmentally-sensitive logging regimes such as Variable Retention (sensu Fedrowitz et al. 2014). At present more than 99% of cutblocks in Mountain Ash forests are logged using the clearcutting silvicultural system and I argue that the adoption of Variable Retention is urgently required. Places that support hollow-bearing trees within forest proposed for logging may provide anchor points for protection around which buffers of uncut forest would be established. There is evidence that variable retention harvesting can improve biodiversity outcomes for small mammals and birds (Lindenmayer et al. 2010, 2015b, 2018), although its effectiveness for species such conservation concern like arboreal marsupials has yet to be demonstrated, in part because of the very long lead time required to recruit new cohorts of large old trees on which these kinds of cavity-dependent species are dependent (Lindenmayer et al. 2017a). Moreover, a switch from clearcutting to variable retention harvesting would have detrimental impacts on biodiversity if it is not accompanied by a significant reduction in sustained yield. This is because of the need to cut more areas of forest (with the potential to further fragment forest landscapes through cutblocks and roads) to meet quotas for sawlogs and pulpwood (Lindenmayer 2017a).

Maintain and restore natural patterns of landscape heterogeneity

Mountain Ash landscapes are dominated by numerous patches of young forest (Fig. 4), but with a clear paucity of large continuous patches of old growth forest. Establishing and maintaining large patches of old growth forest is a critical part of restoring natural patterns of landscape heteroegeneity and therefore restoring Mountain Ash forests. The only tractable way to do this is to withdraw timber harvesting from parts of Mountain Ash forest estate. Previous analyses have identified the climatic and other environmental factors where old growth forest is most likely to develop [places with low levels of incoming solar radiation and in deep protection gullies; (Mackey et al. 2002)] and this provides a useful guide for where to best begin expanding the old growth estate. How much of the Mountain Ash ecosystem should be old growth forest is less clear, but historical levels (prior to European settlement) suggest that between 30 and 60% of the estate was formerly old growth (Lindenmayer et al. 2015a). This provides a useful restoration target. However, given the high risk of future additional fires that typically will be stand-replacing events, the old growth target may need to be significantly above 60% of the forest estate to ensure that eventually the goal of between 30 and 60% old growth can be maintained at any given time.

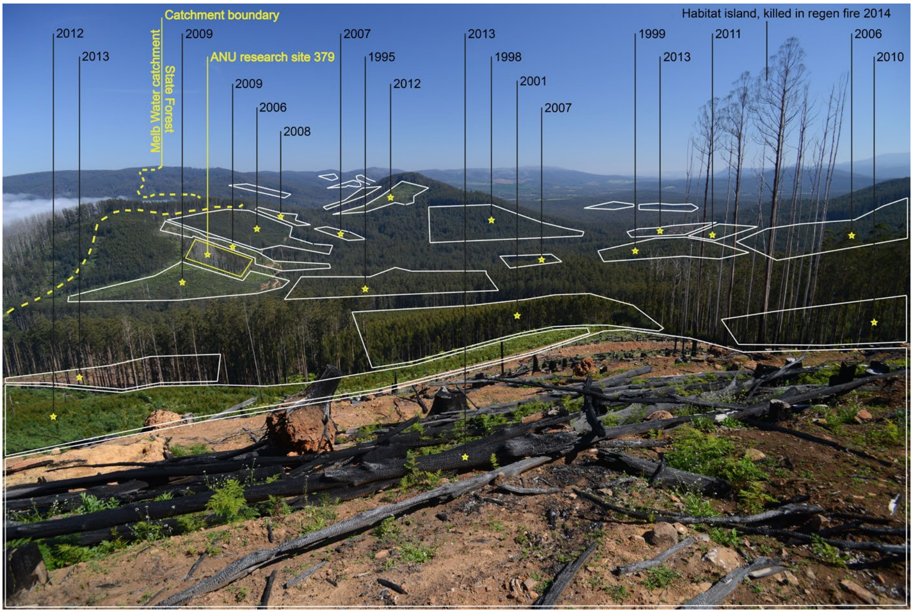

Fig. 4 A typical landscape pattern created by widespread clearcut logging in the Mountain Ash forests of the Central Highlands of Victoria. The landscape is dominated by recently cut forest and young regenerating stands with subsequent major changes in natural patterns of landscape heterogeneity. (Photo by David Blair)

Maintain and restore key ecological processes

As outlined above, two key ecological processes—the natural fire regime and the recruitment of large old hollow-bearing trees—have been significantly altered in Mountain Ash forests. In the case of fire, there is a clear need to reduce the frequency and spatial extent of high-severity wildfires. This is because of their direct negative effects on populations of animals (Lindenmayer et al. 2013), and major negative impacts on habitat suitability including the loss of old growth forest and the reduced abundance of large old hollow-bearing trees (Lindenmayer et al. 2012).

Restoring the fire regime will be major challenge, especially given predictions of increased temperatures and reduced rainfall associated with climate change in the Central Highlands region (Williams et al. 2009). One approach to meeting this challenge will be to expand the old growth estate because fire severity tends to be lower in such areas. Conversely, logged and regenerated forests tend to be at risk of burning at elevated severity (Taylor et al. 2014). The recruitment of large old hollow-bearing trees is another key ecological process that will benefit through the restoration of expanded areas of old growth forest (Lindenmayer et al. 2012). The restoration of this process also will be promoted through the establishment of unlogged forest buffers around existing large old trees.

General discussion

I have outlined four general principles for forest biodiversity conservation and forest restoration and then provided a practical demonstration of how they might be applied through a case study in the Mountain Ash forests of the Central Highlands of Victoria. A complex question in the adoption of strategies that encompass multiple strategies is: *Which of one should have priority for adoption*? I suggest this decision must be based on an understanding of the extent of potential benefits derived from implementing a given principles, or conversely, the impacts of a decision not to adopt that strategy. In the specific case of the Mountain Ash forests, I suggest that while all four principles that I have recommended are important, the maintenance of stand structural complexity should have priority through the protection of all existing large old hollow-bearing trees. This is because these trees are typically between 190 and 400 years old (Lindenmayer et al. 2017a) and the effects of poor management decisions leading to a failure to protect them will take centuries to reverse, with concomitant negative effects on species such as cavity-dependent arboreal marsupials that cannot survive without continued access to these trees.

Synergies between principles

I am acutely aware there are important synergies between the general principles articulated in this paper. Identifying synergies between general principles is important because it highlights where application of one strategy will have positive benefits on others (Fig. 4), thus facilitating the potential to achieve multiple conservation and restoration goals. From a practical perspective, identifying synergies also enables forest managers to optimize the trade-offs in balancing the twin objectives of enhanced biodiversity conservation and wood production. Indeed, by mapping where particular principles (and their manifestation in on-the-ground management) have been implemented in forest landscapes, enables forest managers to determine which actions have priority in what areas and how conservation and production might be integrated.

In the case of the Mountain Ash forests, there are clear synergies in the adoption of all four general principles. For example, efforts to tackle problems with landscape heterogeneity by expanding the old growth estate will inevitably also lead to: (1) the recruitment of more large old hollow-bearing trees (thereby increasing stand structural complexity and tackling the problem associated with the hollow tree recruitment process), and (2) better protect populations of important species of conservation concern such as the Greater Glider. In addition, the establishment of buffers of uncut forest around hollow-bearing trees and known site locations of species such as Leadbeater's Possum and the Greater Glider could provide important nodes for restoration of the old growth forest estate (Fig. 5).

General principles and forest management policies

The use of the general principles outlined in this paper helps guide on-the-ground actions, but also indicates where policy changes and reform is needed. As an example there are currently no policies that specify population targets for existing large old hollow-bearing trees in Mountain Ash forests, nor is there a well articulated strategy for the long-term recruitment of populations of large old hollow-bearing trees. This deficiency urgently needs to be rectified given the rapid and ecosystem-wide extent of the decline of large old

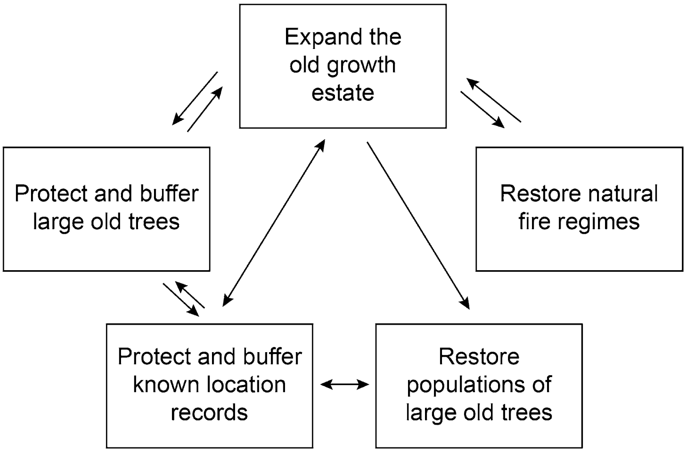

Fig. 5 Interactions between conservation and restoration principles in the Mountain Ash forests of the Central Highlands of Victoria

hollow-bearing trees in Mountain Ash forests (Burns et al. 2015). Robust statistical models of the abundance of hollow-bearing trees (e.g. Lindenmayer et al. 2016a) can help facilitate where in the landscape to target enhanced tree protection and buffering strategies. Another current policy deficiency is the lack of a target for the amount of old growth forest cover to be achieved and then maintained over a specified period. Old growth forest is currently not logged in Mountain Ash forests. However, given the historically low rarity of this growth stage (~1% of the landscape) and the prolonged period of time it takes for new stands of old growth forest to develop, policies are needed now on how much existing regrowth forest needs to be excluded from logging to eventually to become old growth. As outlined earlier in this paper, the achievement of a long-term target of 30–60% old growth may require far more than 60% of the forest estate to be protected.

Embedding general conservation principles and practices in an explicit economic context

The implementation of the biodiversity conservation and restoration principles I have outlined for the Mountain Ash forests comes with some significant policy ramifications. The area of forest available for logging will need to be substantially reduced; in fact much of the estate may well need to be formally reserved to conserve species such as the Greater Glider and Leadbeater's Possum (Taylor et al. 2017; Todd et al. 2016). Policy decisions to increase the amount of reserved forest, increase the old growth estate, improve species protection and tackle problems with altered disturbance regimes have an economic and social cost. These need to be weighed against the social and economic benefits that accrue from employing enhanced conservation and restoration strategies. Indeed, recent work using economic and environmental accounting methods (United Nations 2012) suggest that for the Mountain Ash forests, the economic benefits of increasing forest protection significantly outweigh the economic losses associated with excluded logging from large parts of the forest estate (Keith et al. 2017b). This provides a social and economic framework to help guide the application of the general forest conservation and forest restoration principles that have been articulated in this paper. In addition to setting a large new protected area, one of the most important immediate actions that needs to be implemented is the protection of all existing large old hollow-bearing trees with buffers of unlogged forest (Lindenmayer 2017b). This is because populations of these trees are declining rapidly (Lindenmayer et al. 2012) and they have critical roles not only in conserving cavity-dependent fauna (Lindenmayer et al. 2014) but also in key ecosystem processes such as the storage of carbon (Keith et al. 2009) and rates of seedling germination (Smith et al. 2016). There is no current policy to protect these critically important keystone structures in Mountain Ash forests and this deficiency needs to be rectified urgently.

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