Salvage Logging in the Montane Ash Eucalypt Forests of the Central Highlands of Victoria and Its Potential Impacts on Biodiversity

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Abstract: *The two major forms of disturbance in the montane ash eucalypt forests of the Central Highlands of Victoria (southeastern Australia) are clearfell logging and unplanned wildfires. Since the 1930s wildfire has been followed by intensive and extensive salvage-logging operations, which may proceed for many years after a wildfire has occurred. Although applied widely, the potential effects of salvage logging on native flora and fauna have been poorly studied. Our data indicate that the abundance of large trees with hollows is significantly reduced in forests subject to salvage harvesting. This has implications for the persistence of an array of such cavity-using vertebrates as the endangered arboreal marsupial, Leadbeater's possum (*Gymnobelidues leadbeateri*). Salvage logging also reduces the prevalence of multiaged montane ash forests—places that typically support the highest diversity of arboreal marsupials and forest birds. Limited research has been conducted on the effects of salvage logging on plants; thus, we constructed hypotheses about potential impacts for further testing based on known responses to clearfell logging and key life history attributes. We predict many species, such as vegetatively resprouting tree ferns, will decline, as they do after clearfelling. We also suggest that seed regenerators, which typically regenerate well after fire or conventional clearfelling, will decline after salvage logging because the stimulation for germination (fire) takes place prior to mechanical disturbance (logging). Understory plant communities in salvage-logged areas will be dominated by a smaller suite of species, and those that are wind dispersed, have viable soil-stored seed remaining after salvage logging, or have deep rhizomes are likely to be advantaged. We recommend the following improvements to salvage-logging policies that may better incorporate conservation needs in Victorian montane ash forests: (1) exemption of salvage logging from some areas (e.g., old-growth stands and places subject to only partial stand damage); (2) increased retention of biological legacies on burned areas through variations in the intensity of salvage logging; and (3) reduction in the levels of physical disturbance on salvage-logged areas, especially through limited seedbed preparation and mechanical disturbance.*

Keywords: logging after wildfire, logging impacts on biodiversity, salvage harvesting, southeastern Australia, timber harvesting, wet eucalypt forests

Cosecha de Salvamento en los Bosques Montanos de Eucalipto del Altiplano Central de Victoria y Sus Impactos Potenciales sobre la Biodiversidad

Resumen: *La cosecha de madera y el fuego no controlado son las dos formas principales de perturbación en los bosques montanos de eucalipto en el Altiplano Central de Victoria (sureste de Australia). Desde la década de 1930, los incendios no controlados son seguidos por operaciones intensivas y extensivas de salvamento de madera, que pueden proceder por muchos años después de que ocurrió el fuego no controlado. Aunque aplicados ampliamente, los efectos potenciales de la cosecha de salvamento sobre la flora y fauna nativa han*

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sido escasamente estudiados. Nuestros datos indican que la abundancia de árboles grandes con oquedades se reduce significativamente en bosques sujetos a la cosecha de salvamento. Esto tiene implicaciones para la persistencia de un conjunto de vertebrados que utilizan oquedades, como el marsupial arbóreo Gymnobelidues leadbeateri *en peligro. La cosecha de salvamento también reduce la prevalencia de bosques montanos de edades múltiples – sitios que típicamente soportan la mayor diversidad de marsupiales arbóreos y aves de bosque. La investigación sobre los efectos de la cosecha de salvamento sobre las plantas es limitada, por lo tanto, construimos hipótesis sobre los impactos potenciales para probarlas posteriormente con base en respuestas conocidas a la cosecha de madera y en atributos clave de las historias de vida. Predecimos que muchas especies, como helechos arbóreos con reproducción vegetativa, declinarán, tal como sucede después de la cosecha de madera. También sugerimos que los regeneradores por semilla, que típicamente regeneran bien después del fuego o la cosecha de madera, declinarán después de la cosecha de salvamento porque la estimulación para la germinación (fuego) se lleva a cabo antes de la perturbación mecánica (cosecha de madera). Las comunidades de plantas de sotobosque en áreas con cosecha de salvamento estarán dominadas por un conjunto menor de especies, y es probable que sean favorecidas aquellas que son dispersadas por el viento, que tienen semillas viables almacenadas en el suelo después de la cosecha de salvamento o que tienen rizomas profundos. Recomendamos las siguientes mejoras a las políticas de cosecha de salvamento que pueden incorporar las necesidades de conservación en los bosques montanos de Victoria: (1) exención de cosecha de salvamento en algunas áreas (e.g., bosques maduros y sitios sujetos solo a daños parciales); (2) incremento en la retención de legados biológicos en áreas quemadas por medio de variaciones en la intensidad de la cosecha de salvamento; y (3) reducción de los niveles de perturbación física sobre las áreas con cosecha de salvamento, especialmente la preparación limitada de semilleros y la perturbación mecánica.*

Palabras Clave: bosques húmedos de eucalipto, cosecha de madera, cosecha de salvamento, cosecha después de fuego no controlado, impactos de la cosecha de madera sobre la biodiversidad, sureste de Australia

Introduction

The montane ash forests of the Central Highlands of Victoria in southeastern Australia are dominated by extensive stands of mountain ash (*Eucalyptus regnans* F. Muell.) and alpine ash (*E. delegatensis* R. T. Bak). Mountain ash are the tallest flowering plants in the world and can exceed 100 m in height and 30 m in girth (Ashton 1975). Montane ash forests in the Central Highlands of Victoria are important because they (1) support major timber and pulpwood industries (Gooday et al. 1997) and have considerable economic value (1991 estimation of more than $A250,000 for processed wood products per ha [Macfarlane & Seebeck 1991]), (2) are key areas for the production of water (O'Shaughnessy & Jayasuriya 1991) and produce most of the water for the city of Melbourne (Australia's second largest city), and (3) provide habitat for an array of biota including more than 100 species of birds (Loyn 1985), several hundred plant species (Mueck 1990), and over 30 mammal taxa (Lumsden et al. 1991). The endangered Leadbeater's possum (*Gymnobelidues leadbeateri*) (Lindenmayer & Franklin 2002) and vulnerable Sooty Owl (*Tyto tenebricosa*) and tree geebung (*Persoonia arborea*) (Department of Sustainability & Environment 2005) inhabit these forests.

Approximately 170,000 ha of this forest exist in the Central Highlands of Victoria (Macfarlane & Seebeck 1991). About 30% of the montane ash on public land occurs within the Yarra Ranges National Park and other conservation reserves and is exempt from logging. The remaining (approximately 70%) is broadly designated for wood production, although streamside zones, steep and rocky terrain, and special protection zones for biodiversity protection will not be logged (Commonwealth of Australia and Department of Natural Resources & Environment 1997).

The maintenance of the key values of montane ash forest can be complex because conflicts may exist among, for example, the maintenance of wood production and water-quality services (O'Shaughnessy & Jayasuriya 1991) and the conservation of biodiversity (Lindenmayer & Franklin 2002, 2003). A further complication in these forests is that natural disturbances such as wildfires are often followed by salvage logging (McHugh 1991). Although the impacts of conventional clearfelling have been extensively studied (e.g., Lindenmayer 2000; Ough & Murphy 2004), the potential effects of postfire salvage logging on biodiversity in montane ash forests have received far less attention. We examined possible effects of salvage logging on forest-stand structure and animal and plant responses in the montane ash forests of the Central Highlands of Victoria and make recommendations for improved salvage-logging policies and practices that may better incorporate conservation needs.

Disturbance Regimes in Central Highlands Montane Ash Forests

There are two major forms of disturbance in montane ash forest—natural disturbance (primarily wildfire) and human disturbance (logging). The two are often not independent because fire-damaged stands are typically subject to salvage logging. Other types of natural disturbance in montane ash forests include windthrow and mechanical damage (particularly in the understory) resulting from snowstorms.

Natural Disturbance Regimes

Many major fires have occurred in the Central Highlands over the past 400 years; the largest and most extensive was in 1939. The intensity of wildfires is highly variable (Mackey et al. 2002), and major conflagrations can be stand-replacing events in which virtually all overstory trees are killed. Large areas of predominately even-aged montane ash forest presently characterize the landscape in the Central Highlands. Young seedlings germinate from seed released from the crowns of burned mature eucalypts to produce a new even-aged regrowth stand (Ashton 1976). These processes make it possible to readily determine the age of the dominant overstory in a stand. For example, Lindenmayer et al. (2000*a*) identified nine fire-derived age classes dating from the mid 1700s.

Although high-intensity fires in montane ash forests can largely be overstory-replacing events, they nevertheless leave many kinds of biological legacies. For example, a wide range of plant species survive and resprout vegetatively after wildfires (Ough 2001). Similarly, large-diameter, fire-damaged living and dead standing trees remain in many stands of young regrowth montane ash (Lindenmayer et al. 1991*a*). Such trees contain hollows that provide den and nest sites for many species of arboreal marsupials (Lindenmayer et al. 1991*b*), bats, and birds (Loyn 1985).

Wildfires significantly influence conditions on the forest floor because trees that are killed and collapse become key habitat components for a range of vertebrates (Lindenmayer et al. 2002). Large decaying logs are also important substrates for the germination of rainforest plants (Howard 1973), tree ferns (Ashton 2000), and the development of dense and luxuriant mats of bryophytes (Ashton 1986).

High-intensity overstory-replacing fires represent one disturbance pathway in montane ash forests. Lower-intensity fires lead to partial stand replacement because many trees survive (Smith & Woodgate 1985). Regeneration of young trees in these forests creates multi-aged stands comprising eucalypts of two (and sometimes more) distinct age cohorts (Lindenmayer et al. 1999*a*). The understory is also multiaged in these forests, with plants regenerating from seed after each fire event and others surviving many fires.

Human Disturbance Regimes: Clearfell and Salvage Logging

Logging is the predominant form of human disturbance in montane ash forest, with the conventional harvest method being clearfelling. Virtually all standing trees are removed over 15–40 ha in a single operation. Such coupes can be aggregated in up to 120 ha and harvested over a period of 5 years (Department of Natural Resources & Environment 1996). Logging is followed by burning of logging debris (e.g., bark, tree crowns, and branches), which creates a nutrient-rich ash seedbed that promotes the regeneration of a new stand of eucalypts. The rotation time between clearfelling operations is nominally 80 years (Department of Natural Resources & Environment 2002).

The effects of conventional clearfelling operations (i.e., those not preceded by a wildfire) on biodiversity have been the subject of an array of detailed studies over the past 20 years (e.g., Lindenmayer 2000; Ough 2001), and the impacts of clearfelling include the following. (1) Hollow-bearing trees and their dependent fauna are significantly reduced in abundance (Lindenmayer et al. 1991*a*). An 80-year clearfelling rotation will render large areas of forest unsuitable for cavity-dependent animals. (2) Plant species composition and the trajectory of understory development are significantly altered by clearfelling (Ough 2001). Sedges and seed-regenerating shrub species are more common in clearfelled sites. In contrast, epiphytic ferns and several species of ground fern are depleted and there is a significant decline in long-lived, slow-growing, and slow-to-recruit species such as tree ferns and resprouting shrubs (Ough 2001). (3) Changes in vegetation structure and composition have flow-on effects. For example, the significant loss of tree ferns from clearfelled sites (Ough & Murphy 1996, 2004; Lindenmayer et al. 2000*a*) reduces foraging sites for mammals such as the mountain brushtail possum (*Trichosurus cunninghamii*) (Lindenmayer et al. 1994*b*) and habitat for many epiphytes (Ough & Murphy 1996, 2004). Thickets of long-lived, fire-resistant understory plants are severely depleted or lost after logging (Mueck et al. 1996), including understory rainforest trees (Lindenmayer et al. 2000*b*), which reduces potential nesting sites for birds such as the Pink Robin (*Petroica rosea*) (Loyn 1985).

Clearfelling alters landscape composition, and the limited remaining areas of old-growth forest (now reserved from harvesting) are scattered among extensive stands of young forest recovering after logging. These changes have negative effects on some wide-ranging vertebrates such as the Sooty Owl and yellow-bellied glider, which are strongly associated with large areas of old-growth forest dominated by trees 180 or more years old (Milledge et al. 1991; Lindenmayer et al. 1999*b*). These forests are also important habitat refugia for the mountain brushtail possum and the greater glider. Populations of these species in existing old-growth forests that are fragmented by widespread clearfelling may not be viable in the medium-to-long term (McCarthy & Lindenmayer 1999), although present forest retention policies should allow the area of old growth to increase up to 45% in the coming 150 years in the absence of stand-replacing wildfires.

Although salvage logging has been conducted following windstorms and insect (psyllid) outbreaks in montane ash forests, the majority of salvage operations have taken place after wildfires. Salvage logging occurred after wildfires in 1926, 1932, and 1983. Montane ash forests damaged in the extensive 1939 Black Friday wildfires were salvaged until the late 1950s. Most accessible areas outside the closed water catchments were salvage logged. Noble (1977) noted that "salvage of fire-killed timber went on until the deterioration in logs and the damage being done to regenerating forests called a halt." Salvage logging in montane ash forests is conducted to offset some of the economic losses that incur when high-quality merchantable timber is damaged by fire (McHugh 1991). The sooner the burned trees are removed (preferably within 2 years) the higher their value as timber (Department of Sustainability & Environment 2003). Salvage logging resembles clearfelling, but the disturbance order is reversed. Stands are initially burned by an unplanned wildfire. Fire-damaged stands are then clearfelled with all merchantable timber removed (as described above for conventional clearfelling). The intensity of harvest and size and pattern of logged areas vary according to accessibility and fire intensity. On some occasions eucalypt regeneration is inadequate, and regeneration burns or mechanical site-preparation methods are used to reestablish eucalypt stands.

Whereas the purpose of salvage logging has not changed since the 1930s, harvesting methods have. Teams of bullocks and horses, cable systems, and tramways preceded bulldozers and skidders. Today mechanical harvesters often replace hand felling. Different degrees of physical disturbance are associated with different logging methods—a fact we are mindful of when comparing outcomes from different decades.

Potential Impacts of Salvage Logging

Given that salvage logging typically involves clearfelling, the impacts associated with clearfelling also will characterize salvage-logging operations. Nevertheless, a key issue is whether salvage logging has impacts in addition to those that have been documented for clearfelling (Lindenmayer & Noss 2006). This issue remains unresolved because no specific studies of salvage-logging impacts have been conducted in Central Highlands montane ash forests. Therefore, much of our commentary below is a synthesis of hypothesized effects on animal and plant species and the structure of individual stands.

Impacts on Stand Structure

Franklin et al. (2000) discuss the array of biological legacies that occur in forests and the key ecological roles they play. The biological legacies in naturally disturbed montane ash forests of the Central Highlands of Victoria are no exception in this regard (Lindenmayer & Franklin 2002). Wildfires can promote the development of cavities in large trees in these forests, which provide sheltering, nesting, and foraging sites for more than 40 species of vertebrates (Gibbons & Lindenmayer 2002). Similarly, wildfires and windstorms may generate pulses of large fallen logs (Lindenmayer et al. 1999*c*), and these have an array of ecological roles (reviewed by Lindenmayer et al. 2002).

Both conventional clearfelling operations and salvage logging can result in the depletion or loss of key forms of biological legacies such as large burned logs (Lindenmayer et al. 2002), thickets of vegetation that are semiresistant to fire (Mueck et al. 1996), and large living and dead fire-scarred trees with hollows, which are residual old-growth trees remaining within regrowth stands (Lindenmayer et al. 1990).

The reduction in the abundance of such legacies can have flow-on negative effects on biota that are dependent on them (Ough & Murphy 1996; Lindenmayer & Franklin 2002). Salvage logging can have similar and potentially additional impacts. A major study of the vegetation structure and composition of montane ash stands of different age cohorts was completed by Lindenmayer et al. (2000*a*). That data set allows a close examination of stands that regenerated following the 1939 wildfires. These are the most widespread age cohort in the Central Highlands region and the age class in which logging operations are now confined. Based on historical information on logging activities and known boundaries of several water catchments (where almost no logging has occurred), it is possible to determine where postfire salvage logging took place and where it did not. For the 214 1939-aged sites (each 3 ha in size) where it was possible to unequivocally determine logging history, there was a clear and highly significant difference ($p = 0.004$) in the abundance of trees with hollows in salvaged versus unsalvaged stands (Fig. 1). In a study of mammal response to stand conditions, van der Ree and Loyn (2002) drew conclusions similar to ours about the differences in the abundance of hollow trees between areas of montane ash forest that have and have not been salvage logged.

Differences in hollow-tree abundance between unlogged and salvaged-logged stands of 1939 regrowth are critical for many vertebrates. Other work has established the existence of highly significant relationships between the abundance of trees with hollows in Victorian montane ash forests and the presence and abundance of a range of species of arboreal marsupials, including the endangered Leadbeater's possum (Fig. 2).

Large living and dead trees with hollows in montane ash forests are subject to natural rates of collapse that are estimated to be approximately 4% of the population per annum (Lindenmayer et al. 1990). Although burned hollow trees in stands subject to salvage logging are exempt

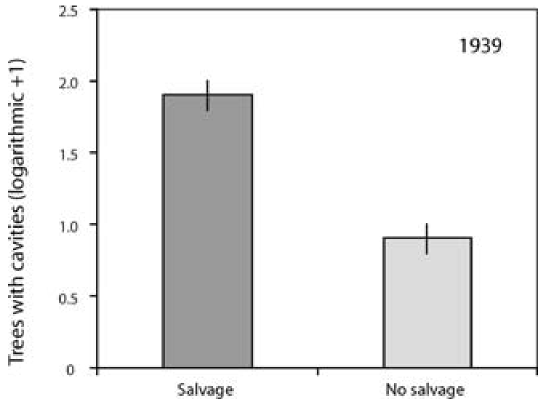

Figure 1. Difference in the abundance of trees with hollows between naturally regenerated and salvaged forest (mountain ash and alpine ash combined) that burned in 1939 fires (214, 3-ha survey sites). Data account for other factors (which are averaged) that significantly influence the abundance of hollow trees in montane ash forests (e.g., slope and topographic position; Lindenmayer et al. 1991a).

from cutting (unless they pose a safety hazard to timber workers), it is likely that their collapse rates are higher because they are subject to increased exposure to altered microclimatic conditions when the remainder of the surrounding stand is cut down (Ball et al. 1999). Such exposure also occurs with conventional clearfelling operations (Lindenmayer et al. 1997).

The development of stand structure in montane ash forests is heavily influenced by both natural and human disturbance regimes. In the case of wildfire, there can be a range of intensities and frequencies that give rise to a wide range of stand conditions (Ough 2001). High-intensity wildfires that occur, on average, every 100–120 years or more frequently (McCarthy et al. 1999) typically result in even-aged montane ash forests (Ashton 1976). Low to moderate fire intensities (Smith & Woodgate 1985) over moderate to long frequencies (>150 years) are more likely to give rise to a multiaged overstory because not all dominant trees are killed (McCarthy & Lindenmayer 1998). Multiaged stands are important because the overall diversity of arboreal marsupials is highest in multiaged stands and several species respond positively to the combination of old trees and dense understory regrowth typical of multiaged forests (e.g., Leadbeater's possum and the mountain brushtail possum; Lindenmayer et al. 1994*a*). In addition, the highest diversity of native, diurnal bird species occurs in multiaged montane ash stands (D.L., et al., unpublished data).

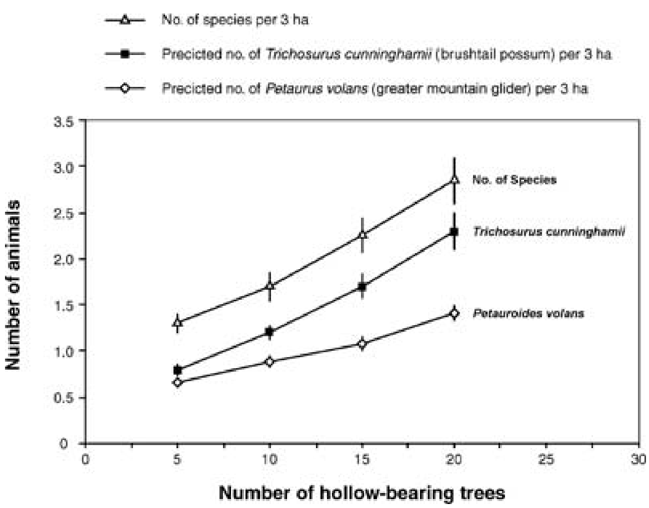

Figure 2. Relationship of the abundance of hollow-bearing trees to the predicted number of species per 3 ha and the abundance of common brushtail possom and greater glider based on poisson regression models of habitat requirements (redrawn from data in Lindenmayer et al. 1990a, 1991c).

Only 9% of montane ash forests in the Central Highlands of Victoria are presently multiaged (Lindenmayer et al. 1991*a*). Results of recent studies show that up to 30% of stands of montane ash burned in the 1939 wildfires may have been multiaged at the time they burned (Lindenmayer & McCarthy 2002). The widespread use of postfire salvage logging following the 1939 wildfires (Noble 1977) means that many of these stands have been converted to largely even-aged forest.

Impacts on Plants

Earlier studies, mostly in mountain ash forests (e.g., Ough 2001), established that the plant species composition and the developmental trajectory of burned (but not salvaged) areas are different from that of clearfelled stands. No studies have specifically examined the impacts of salvage logging on plant communities in montane ash forests of the Central Highlands. The response of many species of plants to salvage logging will vary depending on the intensity of salvage, intensity of wildfire, logging machinery used, composition and proximity of the surrounding vegetation (e.g., as a source of propagules), the interval between wildfire and salvage logging, and the seasons in which wildfire and logging occur. Therefore, we provide generalizations of the sorts of responses that might be expected (Table 1).

Salvage logging within the first few years after wildfire is likely to reduce the survival of many plant species. Salvage logging is a double disturbance in which mechanical disturbance takes place after wildfires have stimulated many plant species to regenerate, either by germinating from seeds or by resprouting. Mechanical disturbance, such as by heavy logging machinery and log movement, will kill many recently germinated or recovering plants.

Several ecologically important taxa, such as tree ferns, normally rely on resprouting to regenerate after wildfire.

Table 1. Hypothesized impacts of salvage logging on plants in the montane ash forests of the Central Highlands of Victoria.

Species	Life form	Most common regeneration strategy after fire	Propagule or organ of regeneration	Likely (initial) population response after wildfire[a]	Likely (initial) population response after salvage logging[b]	Likely (initial) population response after clearfelling[c]
Cirsium vulgare (Savi) Ten.[d]	herb	germinate	seed	increase	further increase (short maturation time and wind dispersed seed)	increase
Hypochaeris radicata L.[d]	herb	germinate	seed	increase	further increase (short maturation time and wind-dispersed seed)	increase
Dianella tasmanica Hook.f.	herb	resprout	rhizome	stable	decline	decline
Sambucus gaudichaudiana DC.	herb	resprout and germinate	deep rhizome, seed	stable	stable	stable
Rubus fruticosus L. agg.[d]	scrambler	resprout and germinate	rhizome, stolon and seed	increase	further increase (animal-dispersed seed, growth from small pieces of detached rhizome, or stolon)	increase
Blechnum cartilagineum Sw.	ground fern	resprout	erect, shallow rhizome	stable, sometimes decline	decline	decline
Polystichum proliferum (R.Br.) Presl	ground fern	resprout	erect, shallow rhizome	stable, sometimes decline	decline	decline
Pteridium esculentum (G. Forst.) Cockayne	ground fern	resprout	long, creeping, deep rhizome	stable	stable or increase (deep rhizome)	stable or increase
Cyathea australis (R. Br.) Domin	tree fern	resprout	terminal bud on trunk	stable	decline	decline
Dicksonia antarctica Labill.	tree fern	resprout	terminal bud on trunk	stable	decline	decline
Cassinia aculeata (Labill.) R.Br.	shrub	germinate	seed	increase	increase if mature populations nearby (wind-dispersed seed)	increase
Correa lawrenceana Hook.	shrub	resprout and germinate	aerial buds, seed	stable	decline	increase (in germinants) but decline in older population (resprouters)
Goodenia ovata Sm.	shrub	germinate	seed	increase	increase, but less than wildfire and clearfelling	increase, but much less than wildfire
Olearia argophylla (Labill.) F.Muell. ex Benth.	shrub	resprout	lignotuber	stable	decline	decline
Olearia phlogopappa (Labill.) DC.	shrub	germinate	seed	increase	increase if mature populations nearby (wind-dispersed seed)	increase
Zieria arborescens Sims	shrub	germinate	seed	increase	decline (or stable if seed store remains)	increase, but less than wildfire

continued

Table 1. (continued)

Species	Life form	Most common regeneration strategy after fire	Propagule or organ of regeneration	Likely (initial) population response after wildfire[a]	Likely (initial) population response after salvage logging[b]	Likely (initial) population response after clearfelling[c]
Lomatia fraseri R.Br.	shrub/small tree	resprout	lignotuber	stable	decline	decline
Bedfordia arborescens Hochr.	tree	resprout and germinate	epicormic buds and seed	stable, sometimes increase	decline	decline
Acacia dealbata Link	tree	Germinate	seed	increase	decline (or stable if seed store remains)	increase
Persoonia arborea F.Muell.	tree	germinate (some resprout)	seed, stem buds	stable or decline	decline	stable or increase (if mature plants present prelogging)
Pomaderris aspera Sieber ex DC.	tree	germinate	seed	increase	decline (or stable if seed store remains)	increase

[a] *Response depends on fire intensity; response given is based on moderate intensity.*
[b] *Assumes logging-free period of at least two decades prior to wildfire and salvage logging, assumes moderate-intensity wildfire.*
[c] *Assumes wildfire-free period of at least two decades prior to logging, assumes logging followed by regeneration burn of introduced species.*
[d] *Introduced species.*

For resprouting species, salvage logging is likely to have effects similar to conventional clearfelling (see Ough 2001). That is, the physical disturbance associated with logging will uproot and damage vegetative propagules, particularly aboveground structures and shallow rhizomes, resulting in reduced survival. Careful mechanical logging during the salvage operation and the reduced need to clear already burned understory for visibility and safety purposes may reduce these impacts.

The main difference between plant community composition after conventional clearfelling and salvage logging is likely to be the additional impact on seed regenerators. Seed regenerators, which typically regenerate well after fire or conventional clearfelling, would be expected to decline after a combination of both (i.e., salvage logging) because the stimulation for germination (fire) takes place prior to the mechanical disturbance (logging). Most species will have not reached sexual maturity in the short time between the two disturbance events. Some individual plants may survive the salvage operation. Nevertheless, recovery of the understory in areas disturbed by salvage operations will largely rely on the seed that remains in the soil seedbank, dispersal from outside the area, and survival of deeply buried rhizomes. Unless further seed can be supplied from the soil-stored seedbank or is dispersed into the area, the representation of these species in newly established stands is likely to decline (Whelan 1995). Species that have a reduced soil-seed store after fire (i.e., all or most of the seed has been stimulated to germinate or has been killed by the fire) rely on canopy-stored seed, or have limited dispersal in from surrounding areas are likely to decline as a result of salvage logging. Conversely, some short-lived herbs may increase due to decreased competition and increased light if maturation time is short and the seed has been set before logging (e.g., *Senecio* spp. and weed species such as *Cirsium vulgare* and *Hypochoeris radicata*). These taxa are likely to decline again as the canopy closes (Appleby 1998).

In summary, plant communities in salvage-logged areas are likely to be dominated by a smaller suite of species, particularly by those that are wind dispersed, have viable soil-stored seed remaining after salvage logging, or have deep rhizomes. Conversely, there will be fewer individuals and taxa that use regeneration strategies such as fire-stimulated germination of soil or canopy-stored seed or resprouting from aboveground or shallow vegetative propagules. The extent of the impact on plant communities will depend on the extent and intensity of mechanical disturbance to the site.

Other Potential Impacts

Neumann (1991, 1992) examined the arthropod fauna of burned and salvaged Mountain Ash forests in the Central Highlands of Victoria and compared it with that of sites subject to clearfell logging and follow-up slash regeneration burns. The work demonstrated large differences in the composition of communities of ants and litter-dwelling arthropods before and after disturbance. Although community composition was altered, Neumann (1991, 1992) speculates that such changes were likely to be relatively short lived. A key problem with this work, however, is the absence of burned but unsalvaged sites for comparison, which limits the extent of inferences that can be made about salvaging impacts.

Discussion

We suggest that the past impacts of salvage logging in montane ash forests, particularly those from the prolonged operations after the 1939 wildfires (Noble 1977), may have been far more substantial than appreciated by many forest managers and conservation biologists. The removal of considerable numbers of large, fire-damaged trees and the loss of many areas of what might have otherwise been multiaged forest (Lindenmayer & McCarthy 2002) has undoubtedly contributed to the shortage of trees with hollows that presently characterizes substantial areas of montane ash forest in the region and is likely to become increasingly problematic in the decades to come (Lindenmayer et al. 1997). Because cavity development in montane ash trees takes more than 120 years (Gibbons & Lindenmayer 2002), the creation of stands with simplified structural conditions by past salvage-logging operations combined with current widespread clearfelling may take hundreds of years to redress. The persistence of many species of hollow-dependent vertebrates within logged areas of montane ash forests during this period will therefore remain a significant conservation issue in the Central Highlands of Victoria (Gibbons & Lindenmayer 2002).

Improved Future Salvage-Logging Policies

The montane ash forests of the Central Highlands of Victoria have been subject to extensive salvage-logging operations such as those in 1939 and 1983. The impacts of conventional clearfell logging methods and the potential effects of salvage logging were not well understood in those times. Nevertheless, the significantly improved current understanding of the biota and dynamics of montane ash forests should be used to inform more ecologically sustainable logging practices, including those applied in salvage-logging operations. In particular, salvage harvesting policies should make provision

(1) for varied salvage-logging intensity, even within large areas of intensely burned forest;
(2) increased retention of biological legacies such as large living and dead trees, large logs, and thickets of unburned or partially burned understory vegetation;
(3) minimized mechanical disturbance;
(4) minimized seedbed preparation;
(5) consideration of timing and season of salvage logging; and
(6) gathering of data to better quantify impacts of salvage logging.

If salvage operations are well planned and carefully managed, both spatially and temporally, they may have reduced impacts on stand structure, plant species composition, and biota in comparison with conventional clearfelling operations that take place in the absence of wildfire. This was the case for more recent salvage harvesting events such as those associated with the 2003 Alpine fires in eastern Victoria, where modified logging prescriptions took account of some of the issues raised above.

Varied Salvage Intensity

Given the present limited understanding of the impacts of salvage logging in montane ash forests, it is important to maintain areas where such practices do not occur and areas where the extent of removal of postfire biological legacies is reduced. This should be the case even where a wildfire has been intense over a large area. The Land Conservation Council (1994) recognized this for the Yarra Ranges National Park, where policies to exclude salvage logging are in place if a wildfire occurs. In locations of montane ash forest outside the national park, some areas should be afforded increased protection from logging and others subject to only low-intensity logging. This is particularly necessary for stands dominated by large, old trees, which are uncommon in wood-production montane ash forests (Lindenmayer et al. 2000*a*).

Old-growth stands are presently exempt from conventional (clearfell) logging and are often located within carefully managed "special protection zones" that have high conservation value within broadly designated wood-production areas (see Macfarlane & Seebeck 1991 for Leadbeater's possum). Notably, a new salvage-logging prescription developed for eastern Victorian alpine ash forest burned in a recent fire (Department of Sustainability & Environment 2003) states that salvage logging will not be undertaken in special protection zones. Stands dominated by large, old trees are critical for several reasons. (1) Large trees in burned old-growth forests have a higher chance of surviving a fire than smaller regrowth trees because of their girth and thicker bark. Hence, burned old-growth forests have a high chance of developing into multiaged stands after a wildfire if salvage logging does not take place. Such multiaged stands would, in turn, be valuable habitat for many species including the endangered Leadbeater's possum (Lindenmayer et al. 1991*c*). (2) The large-diameter trees in burned old-growth forests have a high probability of either containing hollows or developing them after a wildfire (Gibbons & Lindenmayer 2002), thereby providing key sheltering and nesting resources for over 40 species of cavity-dependent vertebrates in montane ash forests. Conversely, the loss of such hollow trees through salvage logging will further contribute to the increasing and prolonged shortage of cavity trees in montane ash forests. (3) Large-diameter living and dead trees in montane ash forests have a significantly higher probability of remaining standing for longer periods of time than smaller-diameter trees (Lindenmayer et al. 1997). This promotes long-term continuity in the availability of key resources such as tree hollows. (4) Even if large, fire-damaged trees collapse soon after a natural disturbance, they play many important ecological roles as fallen logs (Lindenmayer et al. 2002). (5) The understories of old-growth forests are often dominated by tree ferns and other resprouting species. These taxa support large epiphyte populations, and logging activity will result in a decline in the abundance of these taxa (Ough & Murphy 1996, 2004; Ough 2001)

Results of other work suggest where additional salvage exemption zones might be located after future wildfires. Integrated ecological modeling and vegetation structure research show that old-growth and multiaged montane ash forests have a significantly higher chance of occurring in certain parts of landscapes, particularly in areas on flat terrain and sheltered south-facing slopes where the incoming radiation budget is comparatively low (Lindenmayer et al. 1999*a*) because fires have a greater chance of being of lower intensity in these areas. Although many stands in these types of locations are currently even-aged stands as a result of past salvage logging, policies for future postfire logging practices should be reexamined so that future opportunities for multiaged and old-growth stand development can be facilitated. This sort of long-term landscape planning needs to be done well ahead of future major wildfires because management decisions after such events are often made in a "crisis mode," when the environmental values are overlooked or considered to be of secondary importance (Lindenmayer et al. 2004).

If reconstruction analyses by Lindenmayer and McCarthy (2002) are broadly correct, then predicted past levels of multiaged forest (30%) are much lower than they are currently (9%). Given that one of the forms of natural disturbance in montane ash forests is partial stand-replacing fire, a key additional aim of excluding salvage logging from old-growth stands and creating other salvage exemption zones must be to expand the amount of multiaged forest from the current low levels. The objective of such landscape construction work is to create more suitable habitat not only for endangered species, such as Leadbeater's possum, but numerous other species of mammals and birds for which old-growth forest or elements of old-growth stands (particularly large-diameter trees) provide suitable habitat. This recommendation has implications for the regeneration of logged stands because the retention of large trees may suppress the growth of surrounding seedlings and saplings (Incoll 1979). One possible way to minimize this problem and promote levels of stand retention is to create aggregates of retained trees and other vegetation within cutover areas (e.g., Lindenmayer & Franklin 2002). With the support of the Victorian Department of Sustainability & Environment, we have recently commenced an experimental approach to testing the effectiveness of such a strategy in three regions of the Central Highlands (D.L. et al., unpublished data).

Timing of Salvage Logging

Greater consideration should be given to the timing of salvage-logging operations. Operations that continue for prolonged periods after a wildfire have considerable potential to alter forest recovery (Ough 2001). Small germinants will be particularly vulnerable to physical disturbance if logging begins soon after germination. Salvage logging at later growth stages (e.g., 2–4 years after a wildfire) will jeopardize structurally sensitive plant taxa, such as those with easily damaged stems. Conversely, salvage operations that occur too soon after a wildfire may commence before some trees have begun to recover through epicormic shooting. Such live standing trees could mistakenly be assumed to be dead and therefore harvested. Thus, the potential for recovering trees to become part of multiaged stands is reduced. Indeed, researchers studying fire-damaged stands in the Powelltown region of the Central Highlands found many areas that supported living trees recovering after the 1983 wildfires (Smith & Woodgate 1985). However, many of these trees were cut as part of salvage-logging operations, and opportunities for the development of multiaged stands in the area were lost. On this basis, we believe that areas where montane ash trees have not been killed and are beginning to recover after a wildfire should be added to other places (e.g., old-growth stands) that are exempt from salvage logging. Importantly, detailed fire-intensity mapping is now undertaken by the government of Victoria prior to salvage logging to ensure that stands of live trees, or those that are likely to resprout following the fire, are not harvested.

Future Research

All ecologists stress the need for more research in virtually every field of conservation and resource management. Given the scale of recent major natural disturbances (e.g., wildfires, tsunamis, cyclones, and hurricanes) around the world, however, there is an urgent need for detailed research on the impacts of salvage logging on biodiversity. In the case of wildfires, the need for such work is further emphasized by the risk that climate change may lead to increased frequency of major conflagrations and hence more salvage-logging efforts (Spittlehouse & Stewart 2003).

Given that the impacts of salvage logging may exceed those associated with conventional (nonsalvage) logging practices—and last for hundreds of years into the future—current major knowledge gaps must be urgently addressed. In the meantime, modified harvesting prescriptions should be implemented in an attempt to minimize impacts. In the case of plants, the responses we predict will occur for many species (Table 1) should be treated as hypotheses and subject to rigorous testing.

There is also very limited information on the biodiversity values of forests in the initial years after fire. Naturally regenerating forests are important for many types of specialist invertebrates and other fauna (e.g., birds) in forests of the northern hemisphere (reviewed by McIver & Starr 2000), but equivalent work in montane ash forests is limited (Neumann 1991, 1992).

Early planning of future research on salvaging logging is important. Research often is conducted on an ad hoc basis under a crisis-management mentality soon after a major wildfire, and the resulting experimental designs are sometimes poor (McIver & Starr 2000). Research protocols need to be made well before major wildfires occur; thus, experimental designs can then include burned but unlogged sites for comparison with those that are salvaged—a contrast often missing in studies of salvage logging (e.g., Neumann 1991).

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