The adequacy of Victoria's protected areas for conserving its forest-dependent fauna

Chris Taylor[1] and David B. Lindenmayer[1, 2]

[1]Fenner School of Environment & Society, The Australian National University, Canberra, ACT, 2601

[2]Threatened Species Recovery Hub, National Environmental Science Program, Fenner School of Environment & Society, The Australian National University, Canberra, ACT, 2601

Corresponding author

david.lindenmayer@anu.edu.au; Tel 02 61250654

Fenner School of Environment & Society, The Australian National University, 141 Linnaeus Way, Acton ACT 2601.

Running head: Vegetation classes, reserves and disturbance

ACKNOWLEDGEMENTS

The Authors wish to acknowledge the 38 Koori First Nation Clans of Victoria, upon whose respective lands this study was conducted and upon which their Sovereignty was never ceded. We wish to acknowledge their Elders past, present and emerging. Claire Shepherd assisted in editorial and other aspects of production of this paper.

ABSTRACT

Networks of protected areas are a key component of efforts to conserve biodiversity. However, there are concerns about an uncritical focus on the percentage area of reserves without an assessment of how well formal reserves are actually protecting biodiversity. We completed a spatial analysis of the formal reserve system in the Australian state of Victoria. We quantified how well the reserve system captured a crude surrogate for vegetation communities (viz: Ecological Vegetation Classes) as well as distribution models for an array of threatened forest-dependent species. We found evidence of a high degree of overlap between areas subject to intensive forestry (clearcutting) operations and the modelled distribution of a suite of forest dependent species. A key outcome of our study was that areas around sites subject to past logging as well as new areas proposed for logging under the Timber Release Plan in Victoria had significantly higher values for threatened forest dependent species (as determined by habitat distribution models) than areas that had not been logged. We found significant differences in the spatial characteristics of the dedicated reserve systems and informal protected area networks, with the latter featuring much of its area close to a tenure boundary where logging occurs. Our empirical analyses demonstrating the impacts of ongoing logging operations on areas with high environmental suitability for threatened species has important implications. In particular, the current reserve system is inadequate for a suite of forest-dependent taxa, including Critically Endangered Leadbeater's Possum *(Gymnobelideus leadbeateri)* and the vulnerable Greater Glider *(Petauroides volans).* This suggests a high degree of conflict between areas of high value for conservation and areas targeted for wood production.

Key words: Protected areas, disturbance, logging, wet eucalypt forests, threatened species

INTRODUCTION

Many studies have highlighted the rapid decline of the world's biodiversity (e.g. Maxwell et al. 2016; Ceballos et al. 2017; IPBES 2019). Networks of protected areas are a key component of efforts to conserve biodiversity. For example, it has been estimated that approximately 25% of the world's bird biota has been saved from extinction due to conservation reserves (Rodrigues & Brooks 2007). Under key initiatives such as the Aichi targets (among others), there is a concerted push to expand the protected area to 17% of the world's terrestrial surface area, although some scientists argue much higher levels of protection – up to 50% or more – are both needed and feasible for biodiversity protection (Wilson 2016; Dinerstein et al. 2017). While there has been an increase in the extent of protected areas globally, both on land and in the oceans, there have been concerns expressed about an uncritical focus on the percentage area of reserves without an assessment of how well formal reserves are actually protecting biodiversity (Visconti et al. 2019). Indeed, Visconti et al. (2019) highlighted issues with the 'simple use of percentage targets' which have led to perverse outcomes that incentivise the creation of protected areas that have limited conservation and biodiversity value. This problem has long been recognized, for example, under the broad rubric of the so-called "worthless lands hypothesis", in which protected areas are established in those places without value for other human exploits like agriculture, forestry, mining or urban development (Pressey et al. 1993; Lindenmayer & Burgman 2005; Taylor et al. 2017; Venter et al. 2018).

In an effort to counter problems with the bias in reserve systems, the notion of the Comprehensive, Adequate and Representative principles have long been proposed to guide the design of networks of protected areas (JANIS 1997; Commonwealth of Australia 1999; NRMCC 2005). That is, effective reserves should be Comprehensive, Adequate and Representative (CAR) in an attempt to protect the full range of biodiversity in a region. Comprehensiveness refers to the need to include the complete array of biodiversity, ranging from species (and their associated genetic variation) to communities and ecosystems. Adequacy relates to the need to support populations that are viable in the long term. Representativeness means that a reserve system should sample species, vegetation types, communities and ecosystems from throughout their geographic ranges (Margules & Pressey 2000; Lindenmayer & Burgman 2005).

In Australia there has been some expansion of the reserve system in the past few decades, and levels of comprehensiveness have been enhanced (Barr et al. 2016). Nevertheless, Watson et al. (2011) and Venter et al. (2018) found that many of Australia's threatened species either do not occur in reserves or have distributions that fall largely outside of the protected areas network. In forested ecosystems, CAR principles underpin the Regional Forest Agreements that are designed to balance conservation objectives with access to timber and pulpwood for forest industries (DEWHA 2009; DAWR 2017). However, detailed analyses show that the current reserve systems in some RFA areas do not meet CAR principles, particularly in terms of reserve adequacy and the need for protected areas to support viable populations of threatened taxa (Todd et al. 2016; Taylor et al. 2017). This problem has more broadly been identified globally, where the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services report stated that protected areas only partly cover important sites for biodiversity. Therefore, reserve systems are not yet fully ecologically representative and effectively managed (IPBES 2019).

One of the major challenges in designing and establishing reserve systems is that it is simply not possible to document all biodiversity (Gaston & Spicer 2004). Strategic reserve design is therefore based on employing biodiversity surrogates (sensu Lindenmayer et al. 2015b) that are thought to indicate the distribution and or abundance of unmeasured species or other elements of biodiversity (Caro 2010). In the investigation reported here, we sought to assess the extent to which the current reserve system in the Australian State of Victoria captures a suite of forest-dependent threatened species (as determined by developing species distribution models (Elith & Leathwick 2009) for those taxa) across multiple Ecological Vegetation Class (hereafter termed EVCs) Groups. An EVC Group can be loosely defined as one or more vegetation communities with broadly similar floristic, structural, habitat and environmental characteristics where broadly similar ecological processes occur (DELWP 2019a). We also sought to determine levels of human disturbance (primarily logging) within particular EVCs, especially the Wet and Damp Forest EVC Group.

We based this study on three simple questions:

- What is the level of representation of different EVCs in the reserve system in Victoria?
- How well are different threatened species represented in the reserve system?
- What are the spatial configurations of different protected area types across the landscape?

Similar to other areas globally, at the outset of this study, we predicted that EVCs in more productive areas, such as the Wet and Damp Forest EVC Group (where there is potential for large-scale timber and pulp extraction activities such as industrial logging), would be those characterized by the greatest amounts of human disturbance. Often, these productive areas are spatially concentrated, with less productive land more likely to be placed in reserves. This been the case for Victoria, where advocates for native forest logging industry argue that 94 per cent of Victoria's forests on public land are *protected in parks, reserves or land unsuitable for logging*, thereby justifying logging within the remaining 6 per cent (VicForests 2019c). However, environmental values are not evenly distributed across forest types. Similar to previous work, albeit at a larger (national) scale (see Watson et al. 2011; Kearney et al. 2018.), we predicted that many threatened species would not be well conserved by the current reserve system in Victoria. Reserves throughout industrially productive areas can be small and fragmented (Venter et al. 2018). Furthermore, these networks of smaller and fragmented reserves can be exposed to edge effects resulting from adjoining industrial logging operations (Parry 1997; Lindenmayer and Franklin 2002). In this context, the spatial configuration of protected areas is critical to their effectiveness.

The work outlined in this article is a spatial assessment of the current protected area network in Victoria, particularly in regard to the level of protection across EVC groups. It also explores the intersection between the distribution of threatened forest-dependent species and where logging is concentrated. This kind of information is vital for helping to identify areas that should be prioritised for subsequent addition to the dedicated reserve network and is especially relevant in Victoria where recent policies have been implemented to modernize Regional Forest Agreements (RFAs) (DELWP 2019c).

METHODS

We assessed land cover patterns in Victoria by land tenure and Ecological Vegetation Class (EVC) Groups. Using the program Zonation (Moilanen et al. 2005), we then quantified the modelled distributions of threatened species distributions using Habitat Distribution Models (HDMs) in relation to land tenure, EVC Groups and areas where logging is concentrated.

Land Tenure Analysis

We used spatial data from the Australian Collaborative Land Use and Management Program (ACLUMP) to inform our land tenure analysis (ABARES 2011). ACLUMP is a nationally agreed classification system for land use information. It aims to provide a monitoring and evaluation framework, consisting of a three tiered hierarchical structure. The primary tier consists of six classes, which include conservation areas, production from natural environments, dryland agriculture, irrigated agriculture, intensive use and water. The secondary and tertiary classes cover sub-categories, such as specific conservation reserve classifications. ACLUMP uses a spatial reallocation of aggregated data modelling, which included Australian Bureau of Statistics (ABS) census data from which it is partly derived. It also uses the Collaborative Australian Protected Areas Database (CAPAD) and catchment scale land use mapping for Australia. However, limitations of ACLUMP include the absence of land use change over a given period of time, the coarse scale of the datasets (1:2,000,000), and relative standard errors across agricultural land use (ABARES 2011). We cross-validated the ACLUMP dataset with regionally-specific land use maps and vegetation extent obtained through satellite data, along with Forest Management Zones and CAPAD protected area boundaries (Claverie et al. 2018). We corrected errors in spatial data where we detected them.

The CAR reserve system

Under the National Forest Policy Statement (Commonwealth of Australia 1992), Australian federal, state and territory governments agreed to a Comprehensive, Adequate and Representative (CAR) reserve system, which was intended to protect 15% of the pre-1750 distribution of each forest ecosystem (JANIS 1997). It was to consist of *dedicated reserves*, *informal Reserves* and other areas on public land protected by *prescription*. It also included areas of private land by agreement with private landholders. The CAR reserve system formed an important part of the Regional Forest Agreements (RFAs), which were signed between the Australian federal Government and the individual state governments (Department of Agriculture 2015).

Under the dedicated reserve system, protected areas were to be assigned under equivalent categories to those defined by the IUCN Commission for National Parks and Protected Areas (CES 2018). These consist of strict nature reserves (Ia), wilderness areas (Ib), national parks (II), natural monuments or features (III), habitat or species management areas (IV), protected landscapes/ seascapes (V) and protected areas with limited use of natural resources (VI). The IUCN defines a protected area as: *"a clearly defined geographical space, recognised, dedicated and managed, through legal or other effective* *means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values"* (Dudley et al. 2013). In Australia, the Joint ANZECC/MCFFA NFPS Implementation Sub-Committee (JANIS) considered that a dedicated reserve to be an area secured under parliamentary action, either by federal or state/territory governments (JANIS 1997). In Victoria, most dedicated reserves are gazetted under the *National Parks Act 1975*.

The CAR reserve system also includes areas outside of dedicated reserves, which comprise informal protected areas and areas protected under prescription. These informal protected areas are under state forest land tenure and were established under approved forest management plans throughout Victoria and logging prescriptions (DNRE 1998; DEPI 2014a). They were excluded from the dedicated reserve system because the Victorian government did not consider it possible nor practicable to include them into the dedicated reserve network (JANIS 1997). These areas were designated Special Protection Zones (SPZs) and Code of Forest Practices (CFP) Exclusions (DNRE 1998). SPZs were intended to complement the conservation reserve network and to help capture representative samples of vegetation communities, old growth forest, and locations supporting threatened fauna. Logging is currently excluded from these areas, but they are not considered secure, meaning that they are not gazetted under legislation (JANIS 1997). The remaining parts of the CAR reserve system were designated as exclusions areas under the Code of Forest Practices for Timber Production, the regulatory document to which logging in native forests must comply (DEPI 2014a). These exclusion areas consisted of slopes exceeding 30 degrees and streamside buffers, consisting mostly of 40 metres (DELWP 2019b).

We used the Collaborative Australian Protected Areas Database (CAPAD) to inform our analysis of the protected area network, along with forest management zones describing areas outside of the dedicated reserve network (DEE 2016; DELWP 2019b). We described the dedicated reserve network as such in our analysis. For SPZs and Code of Forest Practice

Exclusion areas outside the dedicated reserve network, we described these as informally protected areas in our analysis.

Boundary edge analysis

We explored aspects of the spatial configuration of reserves by conducting a Euclidean distance analysis (Joppa et al. 2008; Crooks et al. 2017) from random points inside dedicated and informal protected areas to their respective tenure boundaries. We generated a Euclidean distance raster in ArcGIS with each internal 50x50m cell occurring within a protected area featuring a distance value in metres from its nearest boundary. We generated a random selection of 20,000 points across the dedicated reserve and informal protected area network and assigned each point with its respective distance from the nearest land tenure boundary. We categorized sample points under their respective protected area type and EVC Group. We used a Tukey's HSD to test for statistical significance between protected area types with regard to the respective distances of points to an edge.

Forest where logging is permitted

Public land outside the CAR reserve system in Victoria is where logging and other industrial activities are permitted under the Code of Forest Practices for Timber Production (DEPI 2014a) and other management standards (DEPI 2014b). Included in the state forest land tenure, this area covers three zones: 1) General Management Zone (GMZ); 2) Special Management Zone (SMZ); and 3) historical reserves (DNRE 1998). General Management Zones are managed for a range of uses, but industrial logging is prioritised. Special Management Zones include areas of high landscape value where logging practices may be modified in an attempt to conserve some of the values. It does not constitute an informal protected area. Logging is also permitted in historic reserves, whereby specific sites of historic importance are to be excluded, but logging can occur around them (DNRE 1998). Where the Code of Practice for Timber Production prohibits logging in GMZs and SMZs, these are designated as Code of Forest Practice Exclusion areas and form part of the informal protected area network (DEPI 2014a).

For our analysis, we used forest management zone data to identify areas of GMZ and SMZ (DELWP 2019b). This was a simplified dataset that did not include Code of Forest Practice Exclusion zones. To identify these, we used a digital elevation model (DEM) to identify slopes greater than 30 degrees and to identify water courses where buffers would have logging operations excluded (EROS 2019).

EVC Groups

For the analysis of native forest areas and other vegetation groups, we used Ecological Vegetation Class (EVC) Group (DELWP 2019d). The EVC Groups dataset was developed by the Victorian Government to categorize the landscape into native woody cover, native grassy cover and native wetland cover, together with probability ratings for a given area to support a particular kind of native vegetation cover. The EVC Groups dataset is a combination of a number of spatial datasets such as tree cover, rainfall and temperature together with time-series LANDSAT imagery and ground-truthed site data. The data set is designed for use at a large scale (1:25,000 to 1:100,000). We used the EVC Group category, which covered 20 vegetation broad native vegetation types, including Wet and Damp Forests, Rainforests, Dry forests, and Mallee EVC Groups. We applied this dataset across all land tenures throughout Victoria.

Logging data

We used historical logging datasets and proposed logging planned under the 2019 Timber Release Plan (TRP) (VicForests 2019b), to analyze the EVC Groups targeted by commercial logging activities (DELWP 2019d). The logging history dataset consisted of LASTLOG 25, which represents the spatial extent of the most recent logging activity recorded for any given area in state forest (DJPR 2019). This data set stores details of the last time an area was known to be logged, the species logged, and the logging method employed. It represents a consecutive overlay of all logging seasons, from 1961-62 season to the logging season 2016-2017. The TRP details the location and the gross area of planned logging, and which is to be undertaken by the Victorian Government owned logging business, VicForests. A TRP covers logging for a period of up to 5 years (VicForests 2019a).

Habitat Distribution Models

We used a subset of unpublished habitat distribution models (HDMs) for 70 species in our analysis (Arthur Rylah Institute unpublished data). These HDMs were developed for, and used by, the Victorian Environment Assessment Council (VEAC) in its assessment of biodiversity values across Victoria. That study identified over 70 species as being solely dependent on native forests for habitat (VEAC 2017) (see Table S1). The species not included were those not dependent on native forests or those found to inhabit other habitat types in addition to native forests (VEAC 2017).

The habitat distribution models were spatially modelled on the environmental characteristics favoured by a given species. Typical environmental attributes included elevation, rainfall, soil type, aspect and slope (VEAC 2017). The analysis further incorporated species-specific modifications, such as tree age for the critically endangered Leadbeater's Possum (*Gymnobelideus leadbeateri*). We used these species habitat distribution models in our spatial prioritisation analysis. The spatial scale of the habitat distribution models consists of a raster grid cell of 75x75m.

Zonation

We used the program Zonation (ver. 4.0) (Moilanen et al. 2005) to identify priority areas across all native forest areas throughout Victoria. Zonation produces a hierarchical ranking of multiple species habitat distribution models over the landscape using a series of algorithms. Zonation's 'core area' algorithm was used to allocate a conservation value to each 75x75m cell across the landscape based on: **(1)** the relative suitability of a cell for each species; **(2)** the weights assigned to species (see below); and **(3)** the proportion of the remaining habitat for each species that the cell represents. In this way, Zonation ranked each cell in the landscape according to how 'irreplaceable' it was for achieving representation of the suitable habitat for each species. In the process of analysis, output cells were proportionately ranked between zero and one. Zonation first removed the least valuable cells from the landscape. The more valuable cells (indicating core areas for species distributions) were removed last in the analysis (Moilanen et al 2014). When a cell was removed, the value across remaining cells increased (Moilanen and Wintle 2006). Areas that contained habitat for rarer species was ranked as highly irreplaceable because habitat for those species was only available in a few or no other place in the landscape.

We produced a series of maps to reflect different habitat distribution model weightings based on the threatened status of the respective species. We allocated weights for the 70 species in relation to their conservation status according to the IUCN Red List, EPBC Act 1999 and the Victorian *Flora and Fauna Guarantee Act 1988*. As there was no best way to weight features, we compared three numerical species weighting scenarios: (1) equal weight (the Zonation default), (2) linear weight, and (3) log weight (Table 1) (Fiorella et al. 2010). The output for the Zonation analysis consisted of a raster grid dataset with each cell across the landscape ranked from zero to one. The highest values cells represented the most suitable habitat areas for the greatest number of species.

We measured the distribution of Zonation priority areas representing suitable habitat for each species within different land tenure categories and forest management zones. We generated a series of 20,000 random points across the EVC Groups throughout Victoria in ArcGIS. Each point contained the Zonation priority value representing suitable habitat distribution for each species in accordance with their respective threatened status weight. The points were grouped into their respective land use tenures. We used a Tukey's HSD to test for the statistical significance of Zonation Values between land tenures for selected EVC Groups, as well as areas around previously logged sites and areas scheduled for logging under the TRP. Statistical significance was noted at $P<0.05$.

RESULTS

Area analysis

The area of Victoria is nearly 23 million hectares (Table 2). The largest land tenure is agriculture, consisting of 13 million hectares or 58% of the State's land area. The next largest are conservation reserves and other protected areas, consisting of 4.4 million hectares or 19% of the state's area. The third largest land tenure area consists of state forests, comprising 14% of the Victoria's land area. Around 1.7 million hectares of state forests is designated under GMZ and SMZ, where logging is permitted. This equates to 8% of the state's total land area.

The dedicated reserve network consists of several large protected areas, with two exceeding 600,000 hectares in size, those being the Murray Sunset and Alpine National Parks (Fig. 1). There are multiple smaller dedicated reserves in the form of 'conservation reserves', such as the 600 hectare Mount Bullfight Conservation Reserve and 47 hectare Seven Acre Rock Natural and Scenic Features Reserve (LCC 1994). The informal protected area network consists of small and fragmented areas located outside the dedicated reserve network. It covers a total area of 1.13 million hectares mostly throughout the eastern half of the state. The land area where logging is permitted is also a fragmented land tenure network, located in between, and adjoining the dedicated reserve and informal protected area networks.

EVC Groups cover an area of 10.3 million hectares and range from the Mallee EVC Group across the semi-arid areas in the Victoria's north west to the Rainforest EVC Group in the cool temperate south east of the State (Fig. 2) (see Appendix S13). The largest areas are dominated by the Dry Forests EVC Group, covering an area of 2.7 million hectares or 26% of the total EVC Group area. The next largest is the Mallee EVC Group, encompassing 1.54 million hectares or 15% of the state's native vegetation classified under the EVC Groups. The next largest is the Wet and Damp Forest EVC Group, which covers 1.35 million hectares (Fig. 3).

The land use categorization of the EVC Groups are variable, with some EVC Groups afforded high levels of protection in the dedicated reserve system. The Mallee EVC Group has 1.12 million hectares or 73% of its total area within the dedicated reserve system (Fig. 3). The Dry Forest EVC Group features the largest area allocated to state forest Land tenure, consisting of 1.3 million hectares or 47% of its total area. The next largest is the Wet and Damp Forest EVC Group, with 799,000 hectares in state sorests, equating to 59% of its total area. It has the largest percentage of its area allocated to state forests of all the EVC Groups.

Protected area boundary analysis

We found that the dedicated reserve network performed better than informal protected areas in terms of the area and shape of each dedicated reserve (Fig. 4). For the Wet and Damp Forests EVC Group, the median distance for a random point inside the dedicated reserve network to a boundary was 1,700m. In comparison the median distance to a boundary for informal protected areas was only 71 metres. We found a statistically significant difference in distance to a boundary between dedicated reserves and informal protected areas across the Wet and Damp Forest EVC Group (Table 3). For the Dry Forest EVC Group, the median distance was 1,232 m for a random point inside the dedicated reserve network to a boundary. The equivalent median distance across the informal protected area network was 180 metres. We found that the Mallee EVC Group scored higher than all other EVC Groups, with a median distance to its respective dedicated reserve boundary of 5,209m.

Across all EVC Groups, we found that the dedicated reserve network overall performed better than informal protected areas, with the median distance for a random point inside the dedicated protected area network to a boundary being 1,756m. In comparison, the median distance to a boundary for informal protected areas was only 150 metres. The *other park* tenure featured a median distance to its respective tenure boundary of 300 metres (Fig. S1). These differences were significant for the sampled EVC Groups as well as the overall EVC Group area (Table 3).

EVC Groups and logging

The Wet and Damp Forest EVC Group has been heavily targeted for logging (Fig. 5; Table S3). Nearly 260,000 hectares or 19% of this EVC Group has been subject to logging, with around 74% of this logged using clearcutting. The EVC Group featuring the least area logged is Mallee, with only 4,617 hectares or 0.3% of its area logged (Table S3).

Zonation habitat distribution prioritisation

Using Zonation analysis, we found the most important areas for forest-dependent threatened species and which supported the greatest amount of suitable habitat occurred in areas designated for logging, with a median equal weight Zonation value of 0.86 (Figs. 6 and 7). The median Zonation values for our linear and log weight analysis were 0.82 and 0.83, respectively (Figs. S2, S3, S5 and, S6). This means that the median cells within land tenure where logging is permitted across state forest were ranked above 82-86% of remaining cells across other forested land tenure in the analysis. The next highest scoring land tenure were the informal protected areas, with a median Zonation values of 0.80, 0.79 and 0.84 for the equal, linear and log weights, respectively (Figs. S4, S5 and S6). Dedicated reserves achieved median Zonation values of 0.71, 0.70 and 0.72 for the equal, linear and log weights, respectively (Figs. S4, S5 and S6). The lowest median Zonation value for all weights was for ‘other state forest’, which is mostly located within the Mallee EVC Group (Figs. S4, S5 and S6). The differences in the range of Zonation values were statistically significant between dedicated reserves, informal protected areas and areas where logging is permitted (Table 4, S4 and S5).

The Wet and Damp Forest EVC Group featured one of the highest median Zonation equal weighted scores in our analysis of 0.90 (Figs. S7, S8 and S9). For specific areas of this EVC Group around previously logged sites and areas scheduled for logging under the TRP 2019, we found a Zonation equal weight value of 0.93 and 0.94, respectively (Fig. 8). Similar trends were noted for the linear and log weights (Figs. S10 and S11). Statistically significant higher ranges in Zonation values were noted for the areas around previously logged sites and areas scheduled for logging compared with areas with no logging or not scheduled for logging (Tables 5 and S6). For the Dry Forest EVC Group, the median Zonation equal weight score was 0.76. For specific areas of this EVC Group around previously logged sites, we also found a similar median Zonation equal weight value of 0.76, but a higher median of 0.87 for areas scheduled for logging under the TRP 2019. Comparably, the Mallee EVC Group featured the lowest median equal weighted Zonation score of 0.1.

DISCUSSION

Assessing the biodiversity value of protected areas is critical to determining their effectiveness or otherwise. It is also crucial for determining priority areas for additions to the existing protected area network. We completed a spatial analysis of the dedicated reserve system in Victoria and its intersection with distribution models for an array of threatened forest-dependent species. As expected, we found that some EVC Groups were poorly protected and others, such as the Wet and Damp Forest EVC Group, having been subject to extensive disturbance such as through clearfell logging. Our analyses also revealed areas previously targeted for logging and those proposed for logging under the recently released Timber Release Plan (VicForests 2019a) in that EVC Group support forests of significantly higher value for threatened forest-dependent species than unallocated forest for logging in the same EVC Group. We further discuss these findings in the remainder of this paper and conclude with some commentary on how to enhance the conservation of forest biodiversity and EVC Groups that have been subject to high levels of logging-generated disturbance.

EVC Groups, levels of protection and human disturbance from logging

Our analyses revealed a distinct bias in the reserve system, with EVC Groups on more productive and economically valuable land afforded lower levels of protection (Fig. 3). This is consistent with previous, broader national-level analyses (e.g. Venter et al. 2018) as well as work in other parts of the world and globally (Scott & Tear 2007).

We found that the dedicated reserve system and the informal protected area network are significantly different, with the former consisting of comparatively larger protected areas and the latter consisting of a small and fragmented network. Most of the informal protected area is close to a land tenure edge. Where these fragmented informal protected areas directly adjoin industrial logging operations, they may be negatively impacted, especially if the logging occurs along multiple boundaries. Distinct edges or boundaries are created between clearcut and unlogged areas, and where profound modifications of biological and physical conditions can occur (Lindenmayer & Franklin 2002). Edge effects can include significant microclimatic changes, such as increased temperature and decreased humidity (Parry 1997). Where the median distance for informal protected areas is as low as 71 metres for the Wet and Damp Forests EVC Group, this network may be subjected to marked edge impacts.

We found evidence of a high degree of overlap between areas subject to industrial logging operations and the modelled distribution of a suite of forest dependent species. Indeed, a key outcome of our study was that areas subject to past logging as well as new areas proposed for logging under the Timber Release Plan in Victoria (VicForests 2019b) had significantly higher values for threatened species (as determined by habitat distribution models) than areas that had not been logged (Figs. 7 and 8). This shows a high degree of conflict between areas of high value for conservation and areas targeted for wood production. Such kinds of conflicts have been observed in forest estates globally (e.g. Lindenmayer & Franklin 2002; Scott & Tear 2007; Visconti et al. 2019). As a useful historical example of a similar outcome, work in south-eastern New South Wales showed that the highest populations of arboreal marsupials were concentrated in relatively small parts of the forest estate that also occurred in places with the highest soil fertility and were preferred areas for logging (Braithwaite et al. 1983; Braithwaite et al. 1988). Collectively, these findings indicate that high productivity areas for tree growth and wildlife habitat provision may also be those places most suited for wood production.

Our empirical analyses demonstrating the impacts of ongoing logging operations on areas with high environmental suitability for threatened species have several important implications. First, past analyses in the Central Highlands region has shown that the current reserve system is inadequate for a suite of forest-dependent taxa, including Critically Endangered Leadbeater's Possum and the vulnerable Greater Glider *(Petauroides volans)* (Todd et al. 2016; Taylor et al. 2017). Indeed, populations of both species are undergoing severe decline, including in reserves (Blair et al. 2018; Lindenmayer & Sato 2018). This means that existing reserves are not adequate, and therefore do not meet one of the core principles of a CAR protected area network. Second, off-reserve management is currently not providing a sufficient complementary contribution to the reserve system for these species (Lindenmayer et al. 2015a; Lindenmayer & Sato 2018). This is important because ongoing logging under the Timber Release Plan will only serve to further erode the suitability of off-reserve areas for biodiversity, especially as such operations will be concentrated in areas with significantly higher predicted values for forest-dependent threatened species than in forests where logging is not occurring. Therefore, ongoing human disturbance generated by logging will likely further exacerbate existing declines in threatened species.

A third key implication of our analyses relates to recent attempts to modernize the Regional Forest Agreements in Victoria (DELWP 2019c). A fundamental tenet of Regional Forest Agreements is to ensure the conservation of forest biodiversity (Department of Agriculture 2015). The information presented in this paper suggests that, as part of modernizing RFAs, areas of the Wet and Damp EVC Group should be among those targeted for addition to the existing dedicated protected area network to promote the conservation of forest-dependent threatened species.

Problems with area as a simple metric for assessing protected area effectiveness

International benchmarks such as Aichi targets set objectives for the percentage of the land surface or the ocean that should be reserved. However, several authors have highlighted the limitations of simple metrics based on percentage area (e.g. Visconti et al. 2019) in part because they fail to account for both the suitability for biodiversity of particular reserves and the viability of populations within such protected areas. In Victoria, forest industry advocates often argue that logging occurs in only a small part of the forest estate and that it will therefore have only limited impacts on other values (such as biodiversity conservation) (VicForests 2019c). Our analyses show, however, that not all areas of forest are created equal in terms of their value for forest-dependent species. For example, nearly 30% in area of the top 10% scoring forest in our analysis occurred on land available to logging (Table S7). Indeed, past logging operations and proposed further logging operations have been concentrated in particular EVC Groups such as those with a high predicted value for a suite of threatened forest-dependent species. Logging operations therefore have a disproportionally higher impact relative to the size of the area within which they occur. Part of the problem with simplistic arguments about the crude size of the area subject to logging is that much of the area of forest in Victoria encompasses environments such as the Mallee EVC Group in north-western Victoria that are both well protected and were never targeted for logging in the first place.

REFERENCES

ABARES (2011) *Guidelines for land use mapping in Australia: principles, procedures and definitions. A technical handbook supporting the Australian Collaborative Land Use and Management Program . 4th Edition*. Australian Government, Canberra.

Barr L.M., Watson J.E., Possingham H.P., Iwamura T. & Fuller R.A. (2016) Progress in improving the protection of species and habitats in Australia. *Biol. Conserv.* **200**, 184-191.

Blair D., McBurney L. & Lindenmayer D.B. (2018) Failing to conserve Leadbeater's Possum and its Mountain Ash forest habitat. *Aust. Zool.* **39**, 443-448.

Braithwaite L.W., Binns D.L. & Nowlan R.D. (1988) The distribution of arboreal marsupials in relation to forest types in the Eden (N.S.W.) woodchip concession area. *Aust. Wildl. Res.* **15**, 363-373.

Braithwaite L.W., Dudzinski M.L. & Turner J. (1983) Studies on the arboreal marsupial fauna of eucalypt forests being harvested for woodpulp and Eden, New South Wales. II. Relationships between the fauna density, richness and diversity and measured variables of the habitat. *Aust. Wildl. Res.* **10**, 231-247.

Caro T. (2010) *Conservation by Proxy. Indicator, Umbrella, Keystone, Flagship, and Other Surrogate Species*. Island Press, Washington D.C.

Ceballos G., Ehrlich P.R. & Dirzo R. (2017) Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines. *Proc. Natl. Acad. Sci. USA* **114**, E6089-E6096.

CES (2018) *State of the Forests 2018 Report*. Commissioner for Environmental Sustainability Victoria, Melbourne.

Claverie M., Ju J., Masek J.G., *et al.* (2018) The Harmonized Landsat and Sentinel-2 surface reflectance data set. *Remote Sens. Environ.* **219**, 145-161.

Commonwealth of Australia (1992) *National Forest Policy Statement*. Australian Government Publishing Service, Canberra.

Commonwealth of Australia (1999) Australian Guidelines for Establishing the National Reserve System. (ed. by E. Australia). Environment Australia, Canberra. available from https://www.environment.gov.au/land/nrs/publications/australian-guidelines-establishing-nrs.

Crooks, K.R., Burdett, C.L., Theobald, D.M., *et al.* (2017). Quantification of habitat fragmentation reveals extinction risk in terrestrial mammals. *Proc. Natl. Acad. Sci. USA* **114**, 7635-7640.

DAWR (2017) Regional Forest Agreements. Australian Government Department of Agriculture and Water Resources, Canberra. Available from http://www.agriculture.gov.au/forestry/policies/rfa. Accessed 20 May 2019.

DEE (2016) Collaborative Australian Protected Area Database. Australian Government Department of the Environment and Energy, Canberra. Available from https://www.environment.gov.au/land/nrs/science/capad/2016. Accessed 29 April 2019.

DELWP (2019a) Bioregions and EVC benchmarks. Victorian Government Department of Environment, Land, Water and Planning, Melbourne. Available from https://www.environment.vic.gov.au/biodiversity/bioregions-and-evc-benchmarks. Accessed 20 May 2019.

DELWP (2019b) Forest Management Zones - Simplified View. Victorian Government Department of Environment, Land, Water and Planning, Melbourne. Available from https://discover.data.vic.gov.au/dataset/forest-management-zones-simplified-view. Accessed 30 April 2019.

DELWP (2019c) Modernising Victoria's regional forest agreements. Victorian Government Department of Environment, Land, Water and Planning, Melbourne. Available from https://www.forestsandreserves.vic.gov.au/forest-management/regional-forest-agreements. Accesses 22 May 2019.

DELWP (2019d) Native Vegetation - Modelled 2005 Ecological Vegetation Classes (with Bioregional Conservation Status). Victorian Government Department of Environment, Land, Water and Planning, Melbourne. Available from https://discover.data.vic.gov.au/dataset/native-vegetation-modelled-2005-ecological-vegetation-classes-with-bioregional-conservation-sta. Accessed 29 April 2019.

Department of Agriculture (2015) *Regional Forest Agreements - an overview and history*. Commonwealth of Australia, Canberra. Available from http://www.agriculture.gov.au/SiteCollectionDocuments/forestry/australias-forest-policies/rfa/rfa-overview-history.pdf.

DEPI (2014a) Code of Practice for Timber Production. Victorian Government Department of Environment and Primary Industries, Melbourne.

DEPI (2014b) Management Standards and Procedures for timber harvesting operations in Victoria’s State forests 2014. Victorian Government Department of Environment and Prmary Industries, Melbourne.

DEWHA (2009) *The Australian Environment Act - Report of the Independent Review of the Environment Protection and Biodiversity Conservation Act 1999*. Australian Government Department of the Environment, Water, Heritage and the Arts, Canberra.

Dinerstein E., Olson D., Joshi A.*, et al.* (2017) An ecoregion-based approach to protecting half the terrestrial realm. *BioScience* **67**, 535-545.

DJPR (2019) Logging history overlay of most recent harvesting activities. Victorian Government Department of Jobs, Precincts and Regions, Melbourne. Available from https://discover.data.vic.gov.au/dataset/logging-history-overlay-of-most-recent-harvesting-activities. Accessed 29 April 2019.

DNRE (1998) Forest Management Plan for the Central Highlands. Victorian Government Department of Natural Resources and Environment, Melbourne.

Dudley N., Sahadie P. & Stolton S., P. Shadie and N. Dudley (2013). IUCN WCPA Best Practice Guidance on (Eds) (2013) *Guidelines for Applying Protected Area Management Categories including IUCN WCPA best practice guidance on recognising protected areas and assigning management categories and governance types*. IUCN, Gland, Switzerland:.

Elith J. & Leathwick J.R. (2009) Species distribution models: ecological explanation and prediction across space and time. *Ann. Rev. Ecol. Evol. S.* **40**, 677-697.

EROS (2019) ASTER Eastern Victoria image retrieved from https://asterweb.jpl.nasa.gov/gdem.asp. Website maintained by the NASA EOSDIS Land Processes Distributed Active Archive Center (LP DAAC) at the USGS Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota.

Fiorella K., Cameron A., Sechrest W., Winfree R. & Kremen C. (2010) Methodological considerations in reserve system selection: A case study of Malagasy lemurs. *Biol. Conserv.* **143**, 963-973.

Gaston K.J. & Spicer J.I. (2004) *Biodiversity: An introduction*. Blackwell Publishing, Oxford.

IPBES (2019) *IPBES Global Assessment Summary for Policymakers*. Intergovernmental Science-policy Platform on Biodiversity and Ecosystem Services (IPBES), United Nations.

JANIS (1997) *Nationally agreed criteria for the establishment of a comprehensive, adequate and representative reserve system for forests in Australia*. Joint ANZECC/MCFFA National Forest Policy Statement Implementation Sub-committee (JANIS), Government of Australia, Canberra.

Joppa L.N., Loarie S.R. & Pimm S.L. (2008) On the protection of "protected areas". *Proc. Natl. Acad. Sci. USA* **105**, 6673 6678.

Kearney S.G., Cawardine J., Reside A.E*., et al.* (2018.) The threats to Australia's imperilled species and implications for a national conservation response. *Pac. Conserv. Biol.*, https://doi.org/10.1071/PC18024.

LCC (1994) Melbourne Area District 2 Review: Final Recommendations. Land Conservation Council, Melbourne. Available from http://www.veac.vic.gov.au/documents/360-Full-Doc.pdf.

Lindenmayer D.B., Blair D., McBurney L. & Banks S.C. (2015a) Ignoring the science in failing to conserve a faunal icon – major political, policy and management problems in preventing the extinction of Leadbeater's possum. *Pac. Conserv. Biol.* **21**, 257-265.

Lindenmayer D.B. & Burgman M.A. (2005) *Practical Conservation Biology*. CSIRO Publishing, Melbourne.

Lindenmayer D.B. & Franklin J.F. (2002) *Conserving Forest Biodiversity: A Comprehensive Multiscaled Approach*. Island Press, Washington DC.

Lindenmayer D.B., Pierson J., Barton P*., et al.* (2015b) A new framework for selecting environmental surrogates. *Sci. Total Environ.* **538**, 1029-1038.

Lindenmayer D.B. & Sato C. (2018) Hidden collapse is driven by fire and logging in a socioecological forest ecosystem. *Proc. Natl. Acad. Sci. USA* **115**, 5181-5186.

Margules C.R. & Pressey R.L. (2000) Systematic conservation planning. *Nature* **405**, 243-253.

Maxwell S., Fuller R.A., Brooks T. & Watson J. (2016) Biodiversity: The ravages of guns, nets and bulldozers. *Nature* **536**, 143-145.

Moilanen A., Franco A.M., Early R.I., Fox R., Wintle B. & Thomas C.D. (2005) Prioritizing multiple-use landscapes for conservation: methods for large multi-species planning problems. *Proc. R. Soc. B* **272**, 1885-1891.

Moilanen A., Pouzols F.M., Meller L., et al. (2014) *Zonation User Manual, Version 4*. C-BIG Conservation Biology Infomatics Group. Department of Biosciences, University of Helsinki, Finland.

Moilanen A. & Wintle B. (2006) Uncertainty analysis favours selection of spatially aggregated reserve networks. *Biol. Conserv*. **129**, 427-434.

NRMCC (2005) *Directions for the National Reserve System – a Partnership Approach*. Natural Resource Management Ministerial Council. Department of the Environment and Heritage, Canberra.

Parry B.B. (1997) Abiotic Edge Effects in Wet Sclerophyll Forest in the Central Highlands of Victoria. Masters Thesis. School of Botany. University of Melbourne, Australia.

Pressey R.L., Humphries C.J., Margules C.R., Vane-Wright R.I. & Williams P.H. (1993) Beyond opportunism: key principles for systematic reserve selection. *Trends Ecol. Evol.* **8**, 124-128.

Rodrigues A.S. & Brooks T.M. (2007) Shortcuts for biodiversity conservation planning: The effectiveness of surrogates. *Ann. Rev. Ecol. Evol. S.* **38**, 713-737.

Scott J.M. & Tear T.H. (2007) What are we conserving? Establishing multiscale conservation goals and objectives in the face of global threats. In: *Managing and Designing Landscapes for Conservation*. (eds D.B. Lindenmayer and R.J. Hobbs), pp. 494-510. Blackwell Publishing, Oxford.

Taylor C., Cadenhead N., Lindenmayer D.B. & Wintle B.A. (2017) Improving the design of a conservation reserve for a critically endangered species. *PLOS One* **12**, e0169629.

Taylor M.F., Fitzsimons J.A. & Sattler P.S. (2014) *Building Nature's Safety Net 2014: A decade of protected area achievements in Australia*. WWF-Australia, Sydney.

Todd C.R., Lindenmayer D.B., Stamation K., Acevedo-Catteneo S., Smih S. & Lumsden L.F. (2016) Assessing reserve effectiveness: Application to a threatened species in a dynamic fire prone forest landscape. *Ecol. Model.* **338**, 90-100.

VEAC (2017) *Conservation values of state forests: Assessment report*. Victorian Environmental Assessment Council, Melbourne.

Venter O., Magrach A., Outram N*., et al.* (2018) Bias in protected-area location and its effects on long-term aspirations of biodiversity conventions. *Conserv. Biol.* **32**, 127-134.

VicForests (2019a) Approved Timber Release Plan 2019. VicForests, Melbourne. Available from http://www.vicforests.com.au/planning-1/timber-release-plan-1/approved-timber-release-plan-april-2019. Accessed 5 May 2019.

VicForests (2019b) Timber Release Plan 2019: Spatial Data. VicForests, Melbourne. Available at http://www.vicforests.com.au/planning-1/spatial-data. Accessed 5 May 2019.

VicForests (2019c) VicForests celebrates Victorian forests on World Forest Day. Media release. VicForests, Melbourne. Available from http://www.vicforests.com.au/latest-news/latestnews. Accessed 25 May 2019.

Visconti P., Butchart S., Brooks T.M*., et al.* (2019) Protected area targets post-2020. *Science* **364**, 239-241.

Watson J.E.M., Evans M.C., Carwardine J*., et al.* (2011) The capacity of Australia's protected-area system to represent threatened species. *Conserv. Biol.* **25**, 324-332.

Wilson E.O. (2016) *Half Earth: Our Planet's Fight for Life*. W.W. Norton, New York.

SUPPORTING INFORMATION

Appendix S1. Range of distance from a random point inside protected area to its boundary across all EVC Groups.

Appendix S2. Linear weight Zonation for forested areas with conservation reserves and historic logging.

Appendix S3. Log weight Zonation for forested areas with conservation reserves and historic logging.

Appendix S4. Equal weight Zonation for and use categories and areas allocated for logging.

Appendix S5. Linear weight Zonation for land use categories and areas allocated for logging.

Appendix S6. Log weight Zonation for land use categories and areas allocated for logging.

Appendix S7. Equal weight Zonation for EVC Groups.

Appendix S8. Linear weight Zonation for EVC Groups.

Appendix S9. Log weight Zonation for EVC Groups.

Appendix S10. Linear weight Zonation prioritisation scores for EVC Group areas subject to clearfell logging.

Appendix S11. Log weight Zonation prioritisation scores for EVC Group areas subject to clearfell logging.

Appendix S12. List of forest dependent threatened species modelled in this study.

Appendix S13. The area of forest and woodland EVC Groups derived from EVC Group dataset.

Appendix S14. Tukey's HSD test for equal weight Zonation.

Appendix S15. Tukey's HSD test for linear Zonation.

Appendix S16. Tukey's HSD test for log weight Zonation.

Appendix S17. Tukey's HSD test for all weights Zonation.

Appendix S18. Area Analysis of the top scoring 10 percent for the equal, linear and log Weight Zonation

Table 1. Three weighting schemes for the species' threatened status used in this study

IUCN Red List Category	Example Species	Equal Weight	Linear Weight	Log Weight
Critically Endangered	Leadbeater's Possum	1	4	0.5
Endangered	Long-footed Potoroo	1	3	0.05
Vulnerable	Greater Glider	1	2	0.005
Near Threatened	Yellow-bellied Glider	1	1	0.0005

Table 2. Areas of different land uses in Victoria with data sourced from ACLUMP (ABARES 2011) and forest management zones (DELWP 2019b)

Land Tenure	**Zone**	**Protection Status**	**Area (ha)**	**% of Total**
Conservation and Parks	Conservation Reserve	Dedicated Reserve	4,404,763	19%
	Other Parks	Other Parks	25,553	0%
	Subtotal for Conservation and Parks		*4,430,317*	*19%*
State Forest	Special Protection Zone	Informal Protection	780,005	3%
	Code of Forest Practice Exclusion	Informal Protection	348,371	2%
	General Management Zone	Logging permitted	1,604,132	7%
	Special Management Zone	Logging permitted	145,692	1%
	Other State Forest	Not Protected	397,904	2%
	Subtotal for State Forests		*3,276,105*	*14%*
Historic Reserve	Other Parks	Logging permitted	38,633	0%
Agriculture	Agriculture	Private Land	13,250,902	58%
Plantation	Plantation	Private Land	571,570	3%
Intensive	Urban and Intensive Use	Private Land and Roads	992,481	4%
Mining and Waste	Industrial	Private Land	43,915	0%
Water	Environment/Services	Private/Public	120,668	1%
Other Land Use	Miscellaneous	Private/Public	114,822	1%
Total			22,839,413	100%

Table 3. Tukey's HSD test for random points inside the protected area network to a boundary for Wet and Damp Forests, Dry Forest, and Mallee EVC Groups (P<0.05)

EVC Group	Reserve Type Comparison	diff	lwr	upr	p
Dry Forest	Informal Protected Area-Dedicated Reserve	-1667.859	-1769.456	-1566.262	0
Mallee	Other Parks-Dedicated Reserve	-6745.794	-11743.58	-1748.004	0.008
Wet and Damp Forest	Informal Protected Area -Dedicated Reserve	-2129.195	-2266.436	-1991.953	0
Overall EVC Groups	Informal Protected Area -Dedicated Reserve	-3184.3398	-3346.514	-3022.165	0
	Other Parks-Dedicated Reserve	-3170.047	-4196.977	-2143.117	0
	Other Parks-Informal Protected Area	14.29282	-1019.842	1048.428	0.999

Table 4. Tukey's HSD test for equal weight Zonation results between land tenures and forest management zones. Bold text denotes statistical significance P<0.05).

Land Tenure Comparison	diff	lwr	upr	p adj
Informal Protected Area-Dedicated Reserve	**0.191**	**0.173**	**0.208**	**0.000**
Logging Permitted-Dedicated Reserve	**0.224**	**0.210**	**0.239**	**0.000**
Other Parks-Dedicated Reserve	-0.109	-0.232	0.015	0.122
Other State Forest-Dedicated Reserve	**-0.133**	**-0.161**	**-0.106**	**0.000**
Private Land-Dedicated Reserve	0.002	-0.014	0.019	0.998
Logging Permitted-Informal Protected Area	**0.034**	**0.014**	**0.053**	**0.000**
Other Parks-Informal Protected Area	**-0.299**	**-0.424**	**-0.175**	**0.000**
Other State Forest-Informal Protected Area	**-0.324**	**-0.355**	**-0.293**	**0.000**
Private Land-Informal Protected Area	**-0.188**	**-0.210**	**-0.167**	**0.000**
Other Parks-Logging Permitted	**-0.333**	**-0.457**	**-0.209**	**0.000**
Other State Forest-Logging Permitted	**-0.358**	**-0.387**	**-0.329**	**0.000**
Private Land-Logging Permitted	**-0.222**	**-0.241**	**-0.203**	**0.000**
Other State Forest-Other Parks	-0.025	-0.151	0.101	0.994
Private Land-Other Parks	0.111	-0.013	0.235	0.110
Private Land-Other State Forest	**0.136**	**0.105**	**0.166**	**0.000**

Table 5. Tukey's HSD test for equal weight Zonation results between areas previously clearfell logged post 1970, areas scheduled for clearfell logging under the 2019 Timber Release Plan and remaining EVC Group area not logged. Bold text denotes statistical significance P<0.05.

EVC Group	*Sequence*	*Diff*	*Lower*	*Upper*	*P adj*
Wet and Damp Forest	**Remaining Area of EVC Group/Previously Logged**	**0.044**	**0.029**	**0.058**	**0.000**
Wet and Damp Forest	**Remaining Area of EVC Group /TRP 2019**	**0.057**	**0.030**	**0.083**	**0.000**
Wet and Damp Forest	Previously Logged/TRP 2019	0.013	-0.016	0.042	0.546
Dry Forest	**Remaining Area of EVC Group/Previously Logged**	**0.079**	**0.045**	**0.113**	**0.000**
Dry Forest	**Remaining Area of EVC Group /TRP 2019**	**0.108**	**0.034**	**0.182**	**0.002**
Dry Forest	Previously Logged/TRP 2019	0.029	-0.052	0.109	0.685
All Forest EVCs	**Remaining Area of EVC Group/Previously Logged**	**0.246**	**0.218**	**0.274**	**0.000**
All Forest EVCs	**Remaining Area of EVC Group /TRP 2019**	**0.256**	**0.199**	**0.312**	**0.000**
All Forest EVCs	Previously Logged/TRP 2019	0.010	-0.053	0.073	0.925

FIGURES

Fig. 1. Land tenure and forest management zones across Victoria

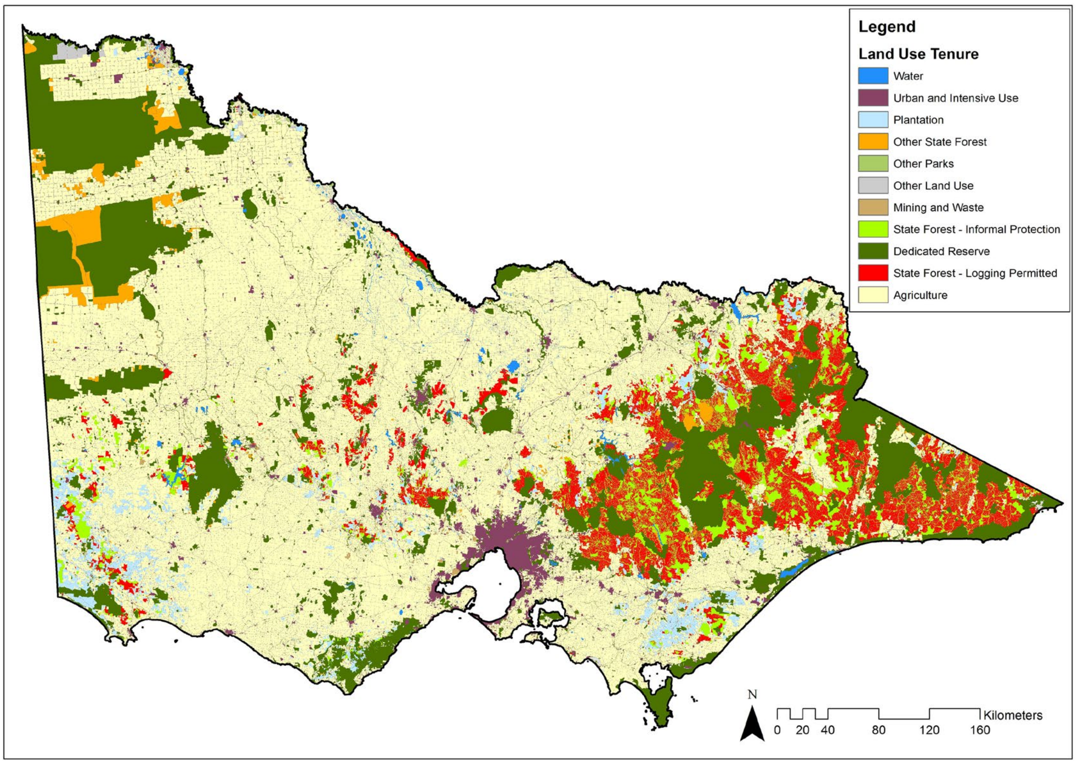


Fig. 2. Ecological Vegetation Class (EVC) Groups, conservation reserves and historic clearcutting

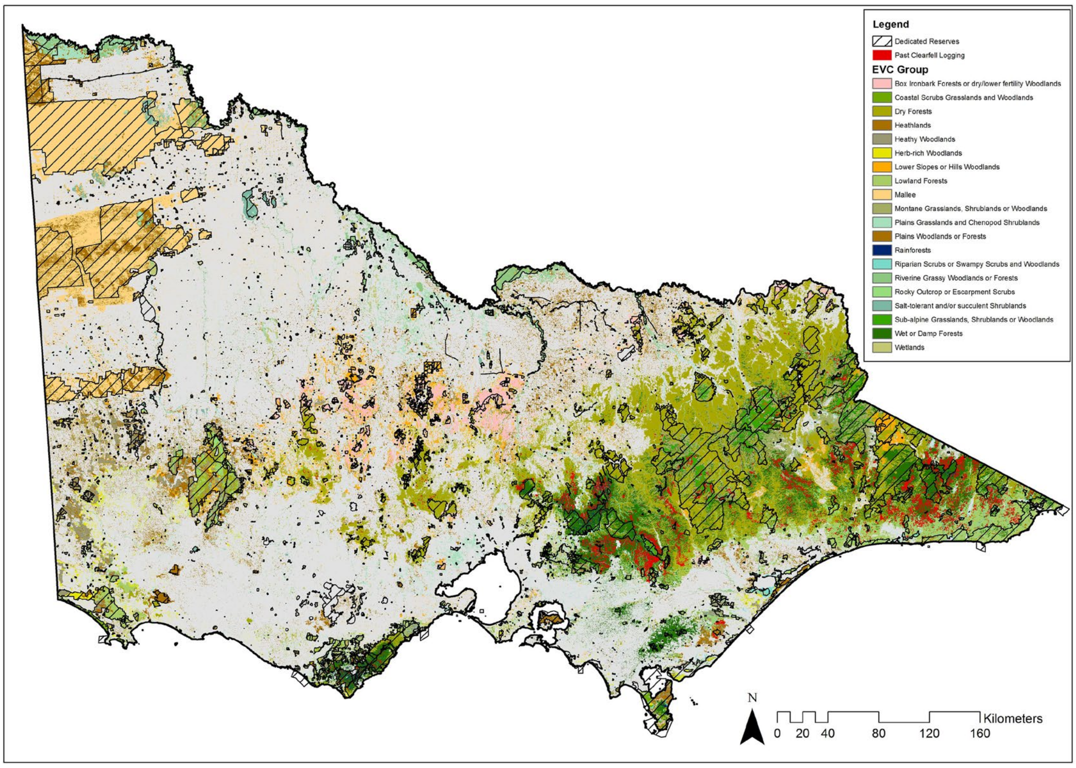


Fig. 3. EVC Group and land tenure classification by area

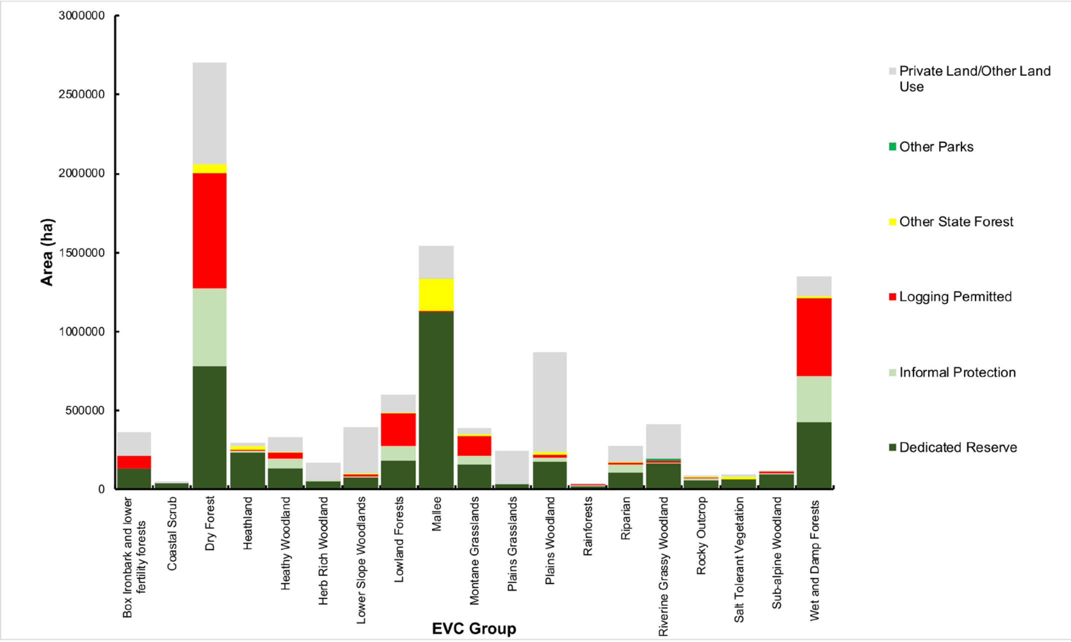


Fig. 4. Range of distance from a random point inside protected area to its boundary for the Dry Forest EVC Group (left), the Mallee EVC Group (centre) and the Wet and Damp EVC Group (right)

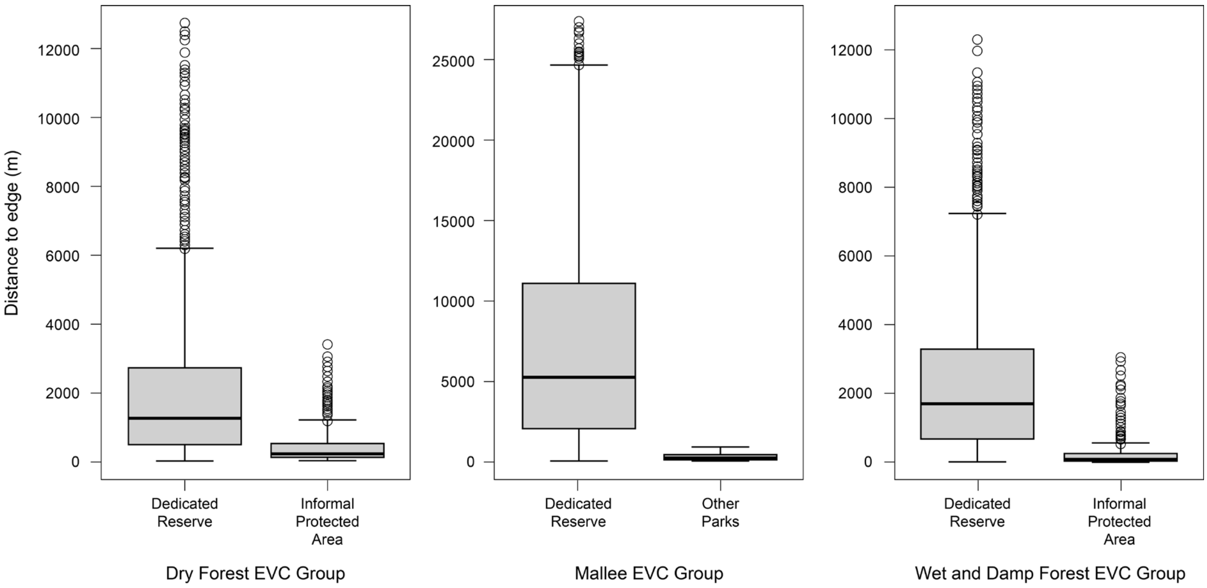


Fig. 5. Historic logging across the EVC Groups

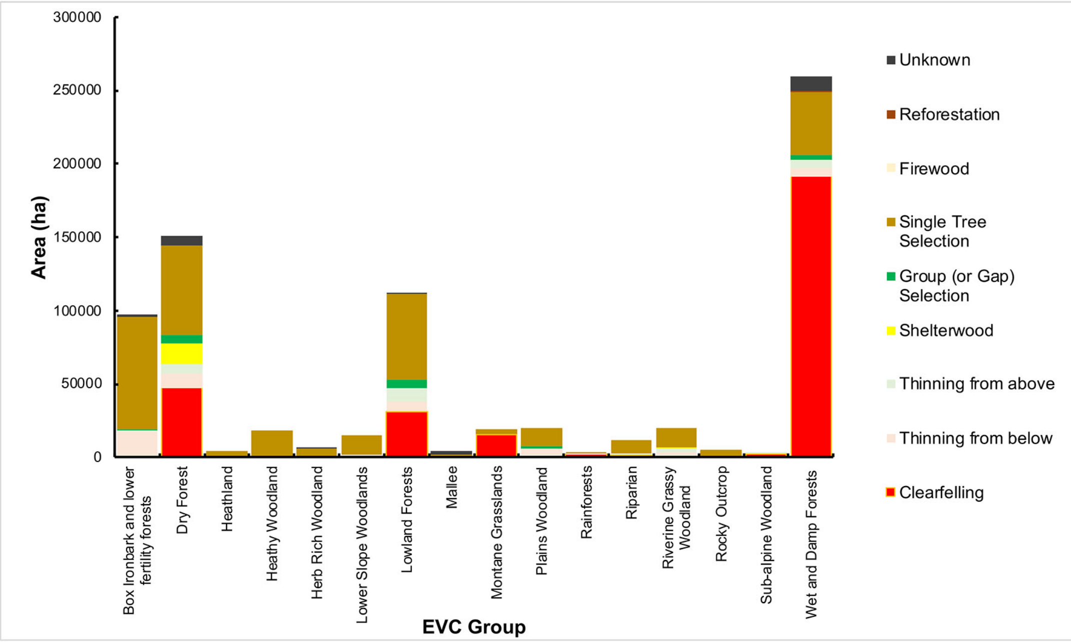
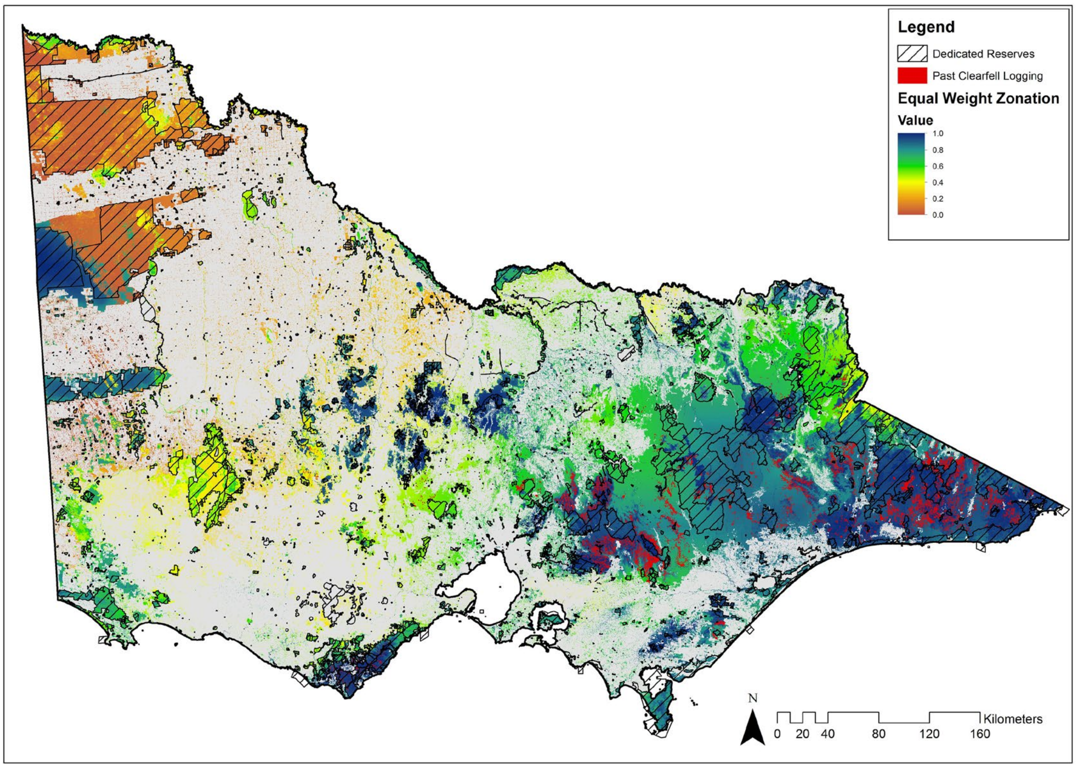


Fig. 6. Equal weight Zonation for forested areas with conservation reserves and historic logging overlaid



674

Fig. 7. Equal weight Zonation scores for selected land tenure across Victoria

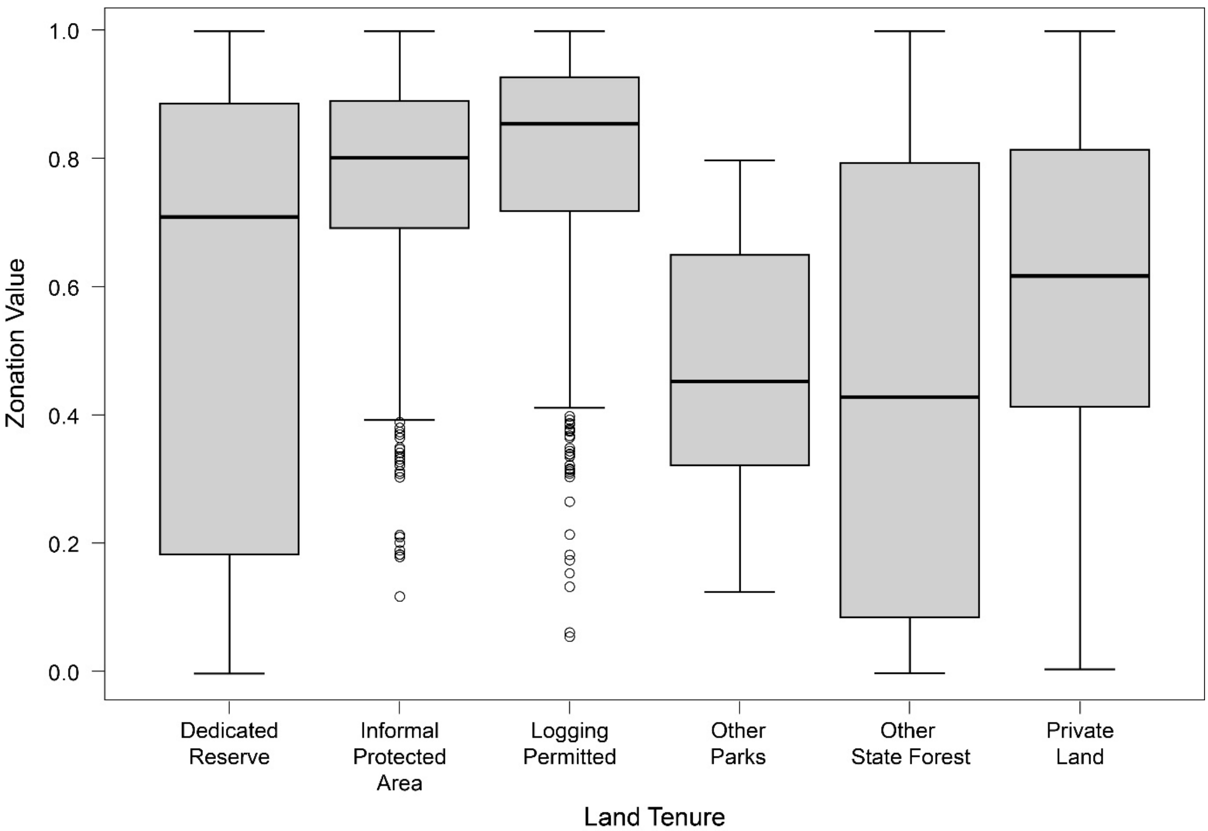
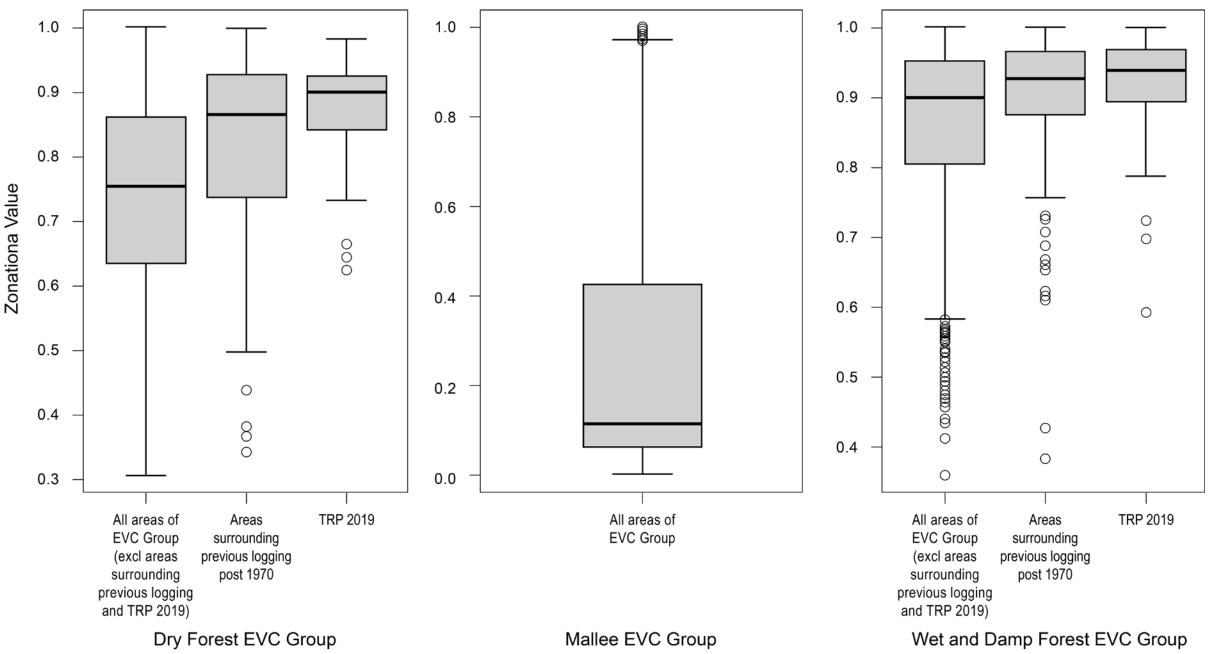


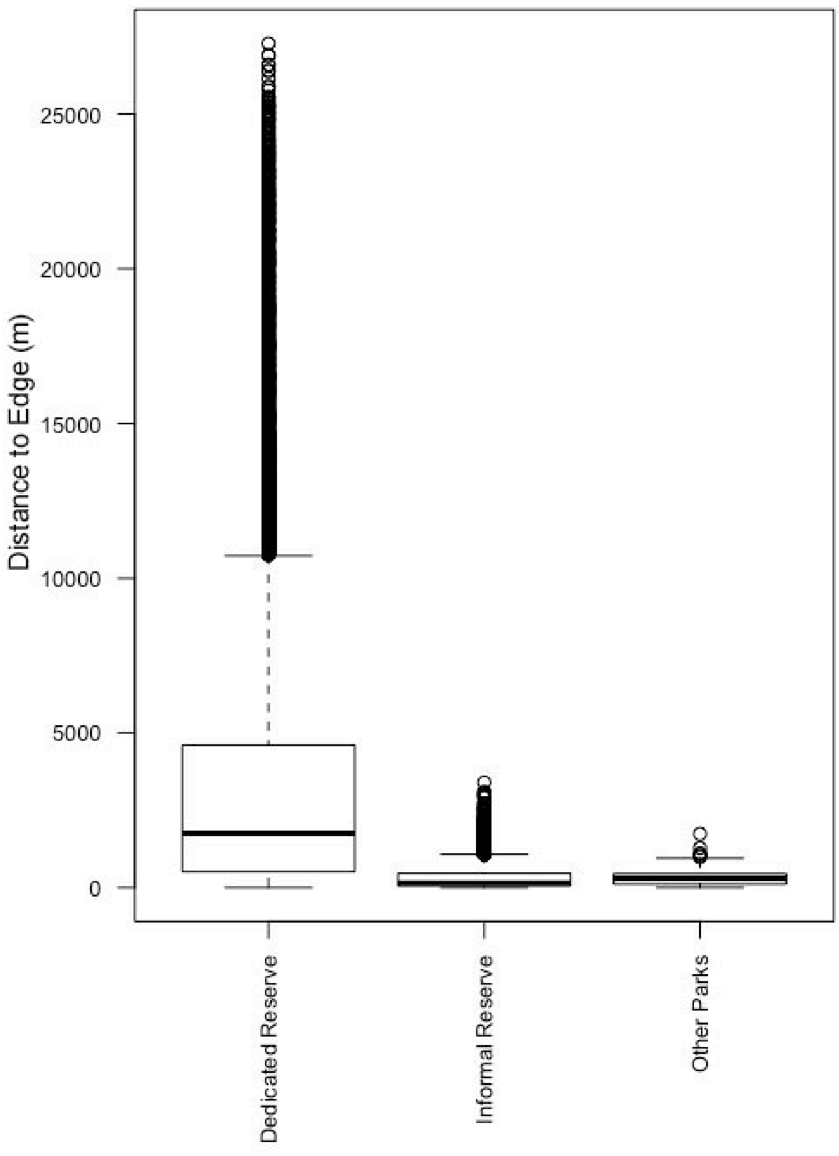
Fig. 8. Equal Weight Zonation prioritisation scores for selected EVC Groups



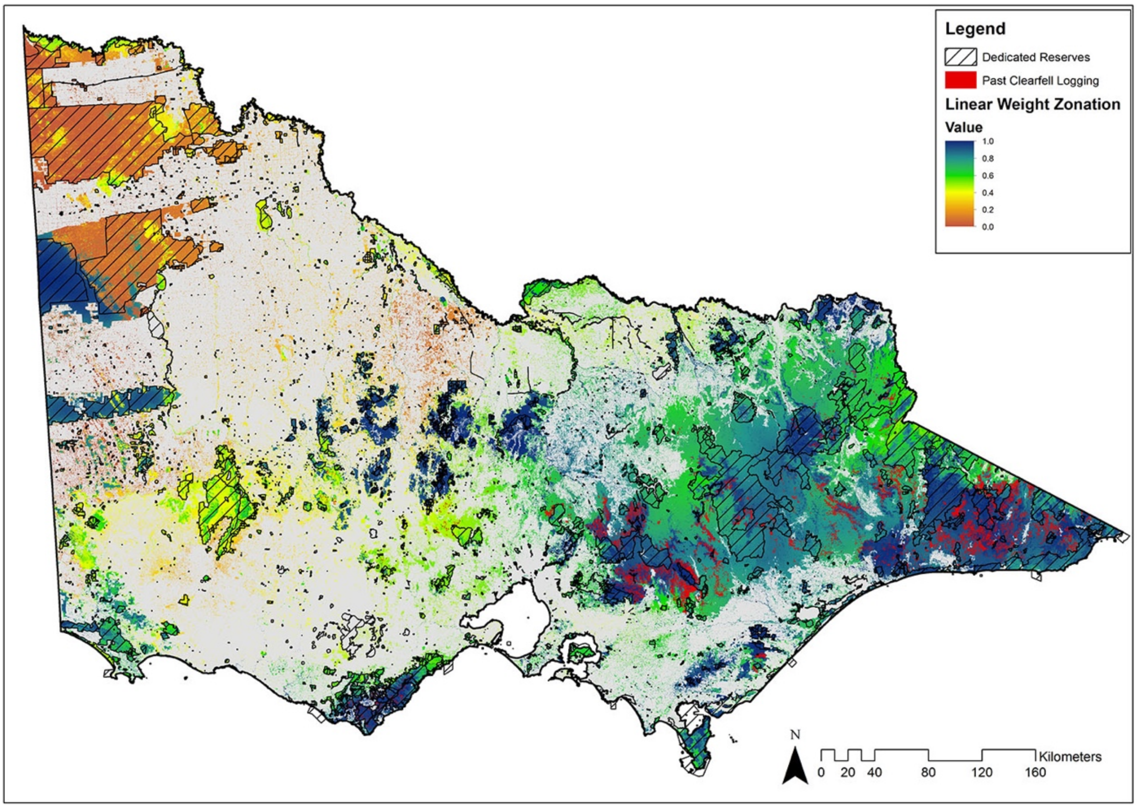
675

The adequacy of Victoria's protected areas for conserving its forest-dependent fauna

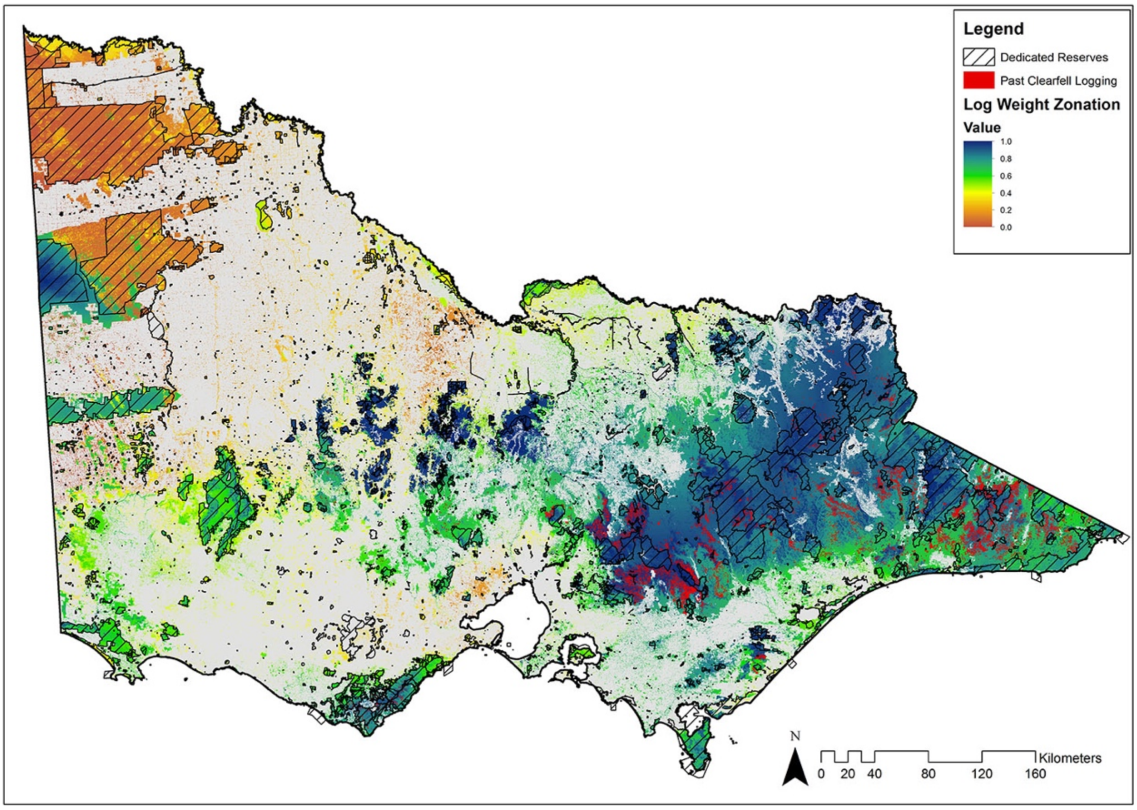
SUPPORTING INFORMATION



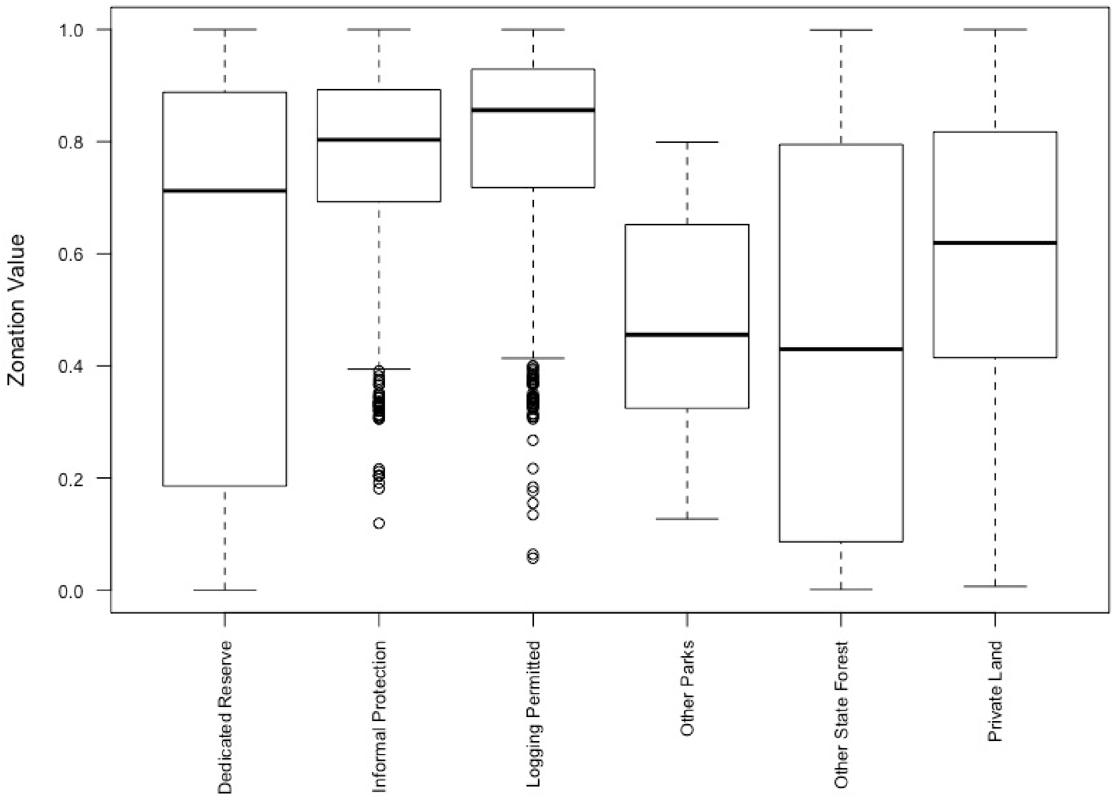
Appendix S1. Range of distance from a random point inside protected area to its boundary across all EVC Groups



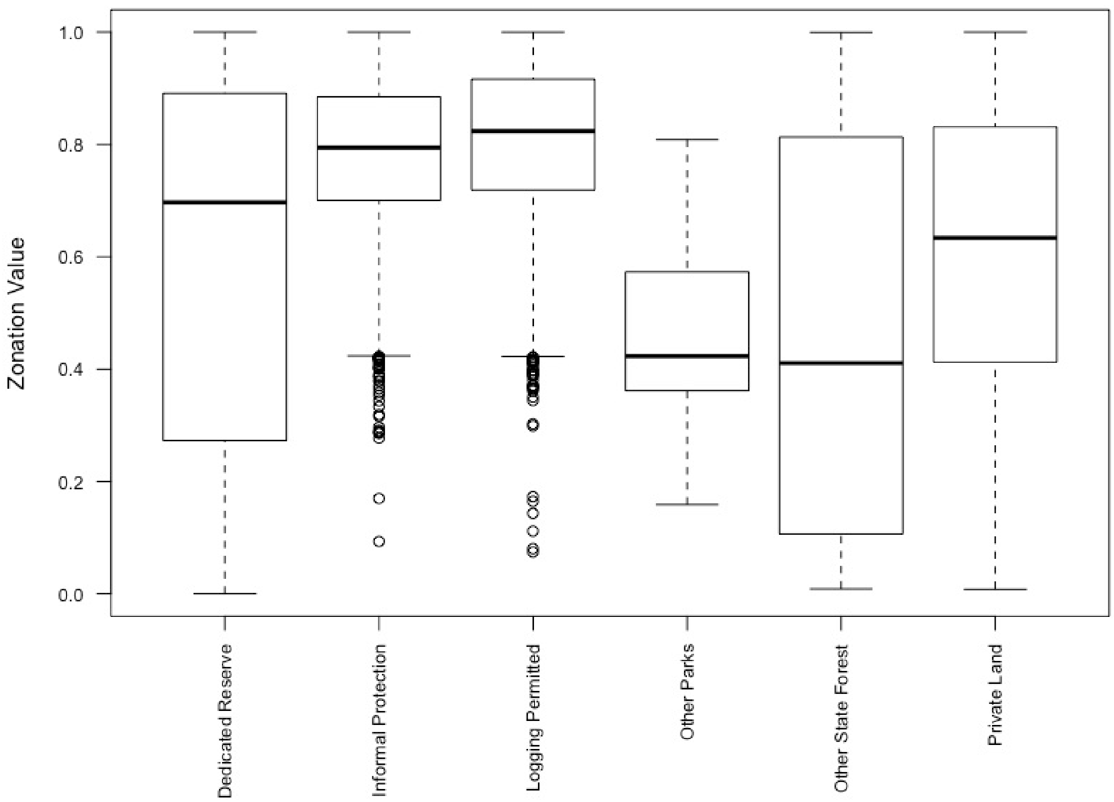
Appendix S2. Linear weight Zonation for forested areas with conservation reserves and historic logging overlaid



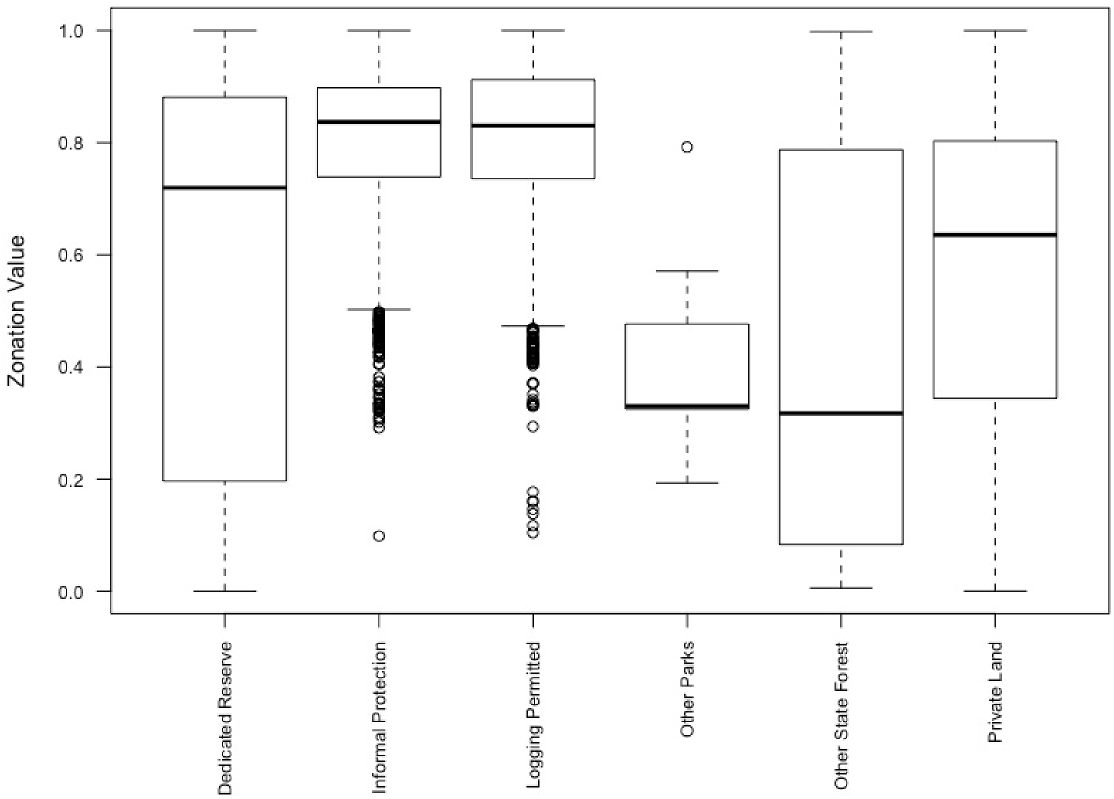
Appendix S3. Log weight Zonation for forested areas with conservation reserves and historic logging overlaid



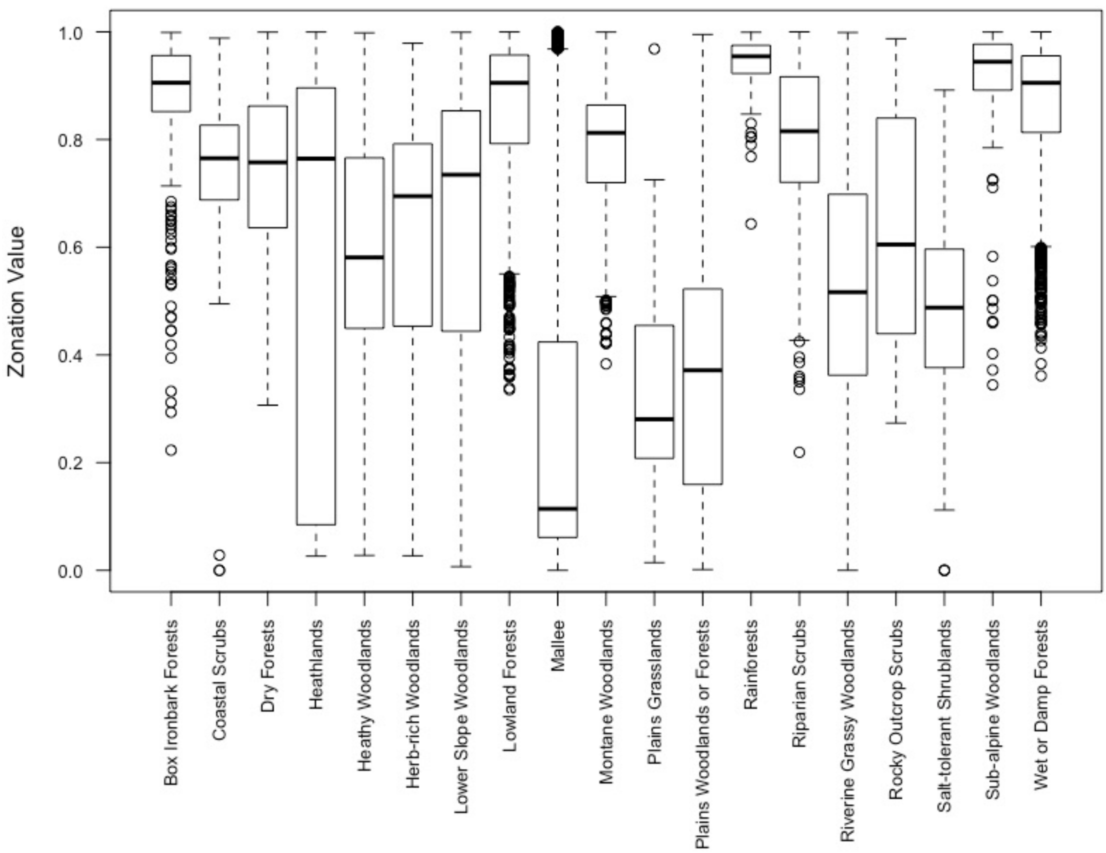
Appendix S4. Equal weight Zonation for ACLUMP derived land use categories and areas allocated for logging



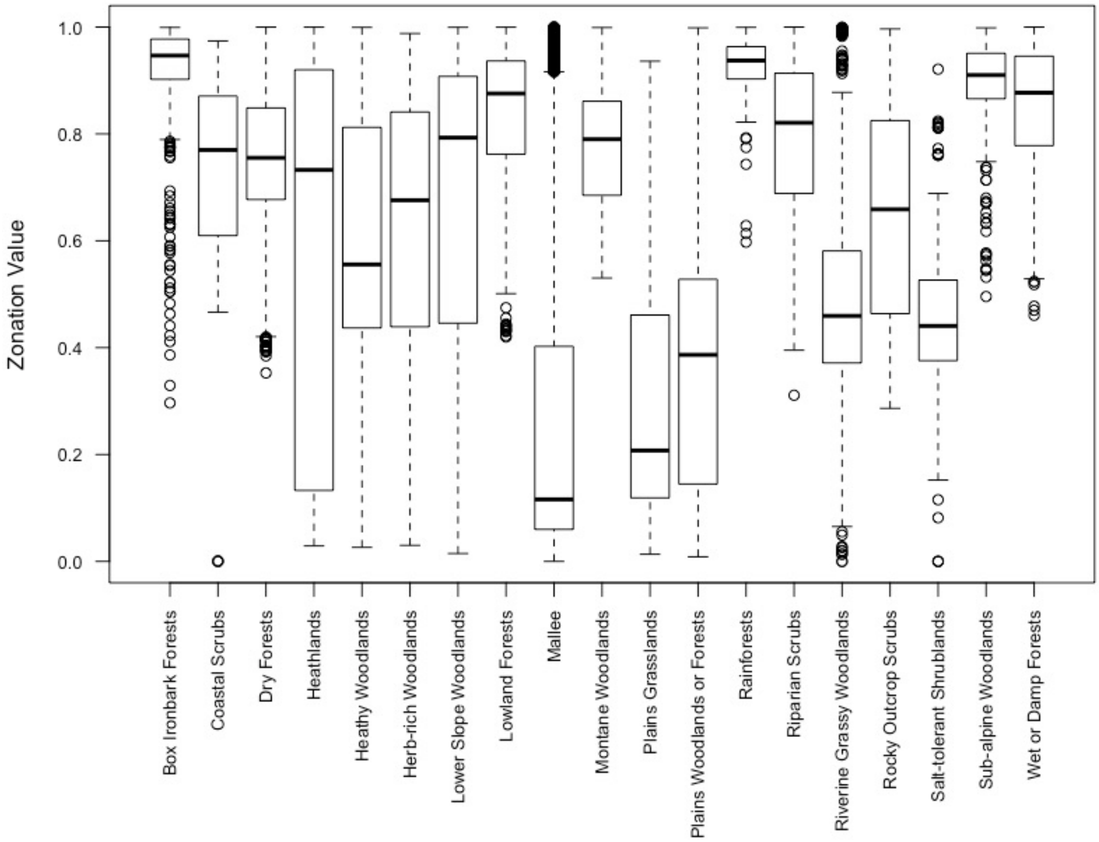
Appendix S5. Linear weight Zonation for ACLUMP derived land use categories and areas allocated for logging



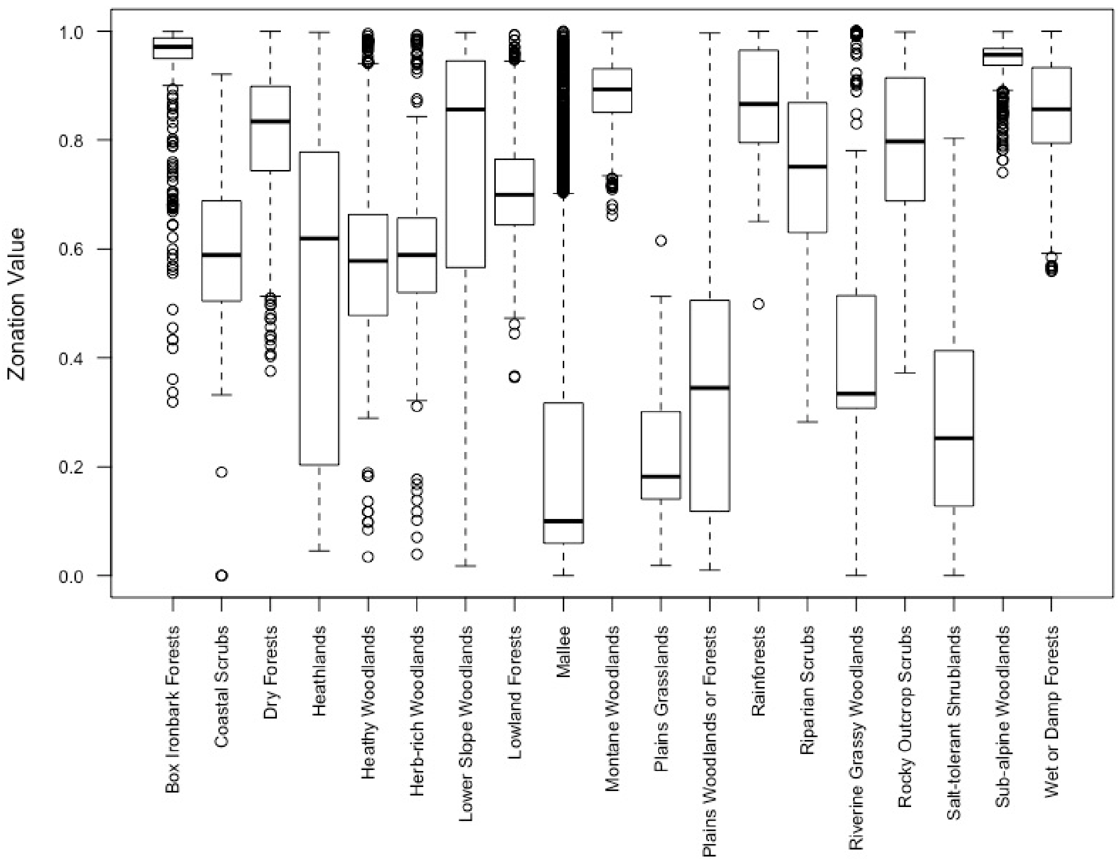
Appendix S6. Log weight Zonation for ACLUMP derived land use categories and areas allocated for logging



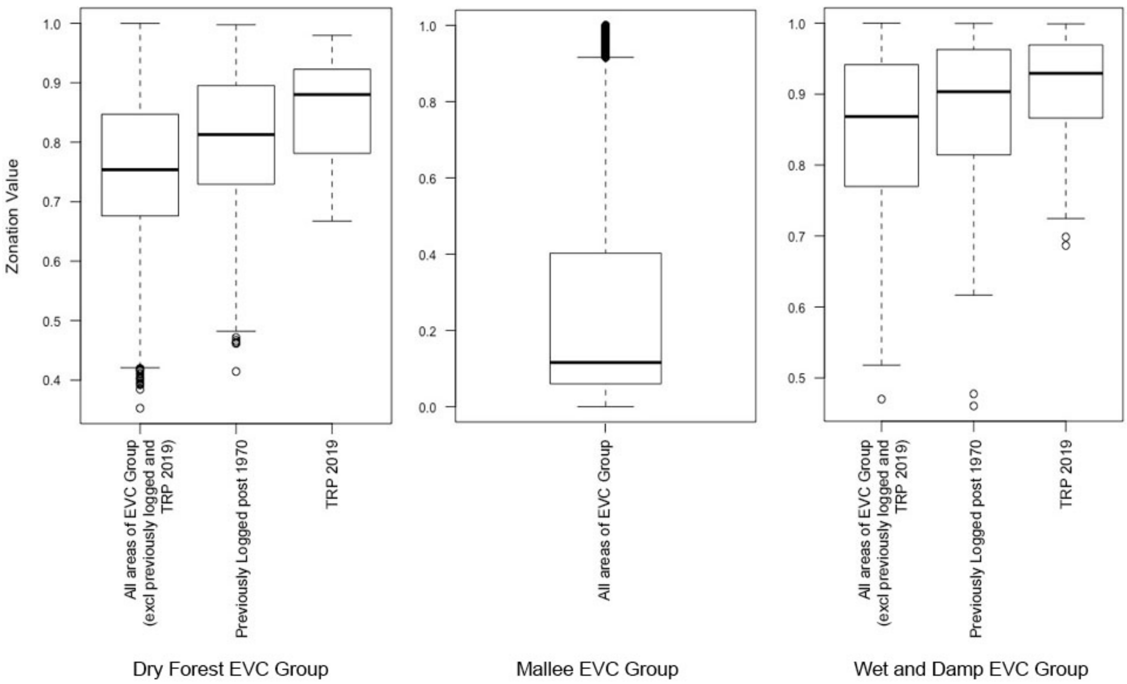
Appendix S7. Equal weight Zonation for EVC Groups



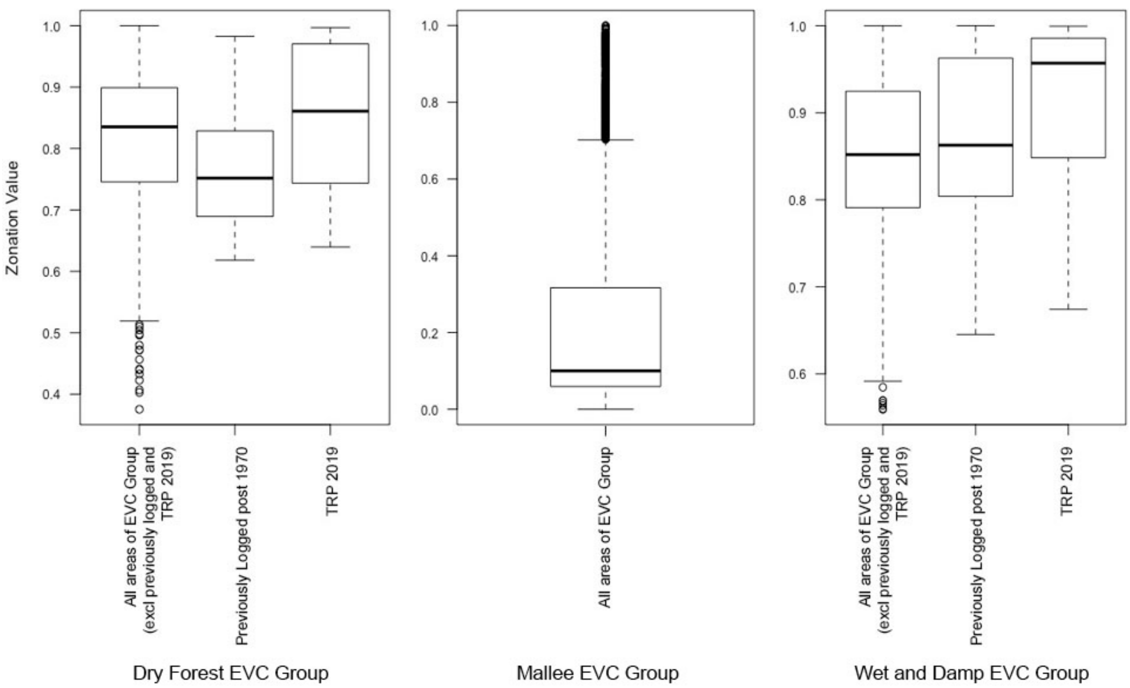
Appendix S8. Linear weight Zonation for EVC Groups



Appendix S9. Log weight Zonation for EVC Groups



Appendix S10. Linear weight Zonation prioritisation scores for Dry Forest EVC Group (left), Mallee EVC Group (middle) and Wet or Damp Forest EVC Group (right) subject to clearfell logging



Appendix S11. Log weight Zonation prioritisation scores for Dry Forest EVC Group (left), Mallee EVC Group (middle) and Wet or Damp Forest EVC Group (right) subject to clearfell logging

Appendix S12. List of forest dependent threatened species modelled in this study

Common name	Scientific name	Broad	Focus	EPBC	Vic Stat	FFG
Spot-tailed Quoll	*Dasyurus maculatus*	•	•	E	E	L
Brush-tailed Phascogale	*Phascogale tapoatafa*	•			V	L
Swamp Antechinus	*Antechinus minimus*	•		V	NT	L
White-footed Dunnart	*Sminthopsis leucopus*	•			NT	L
Greater Glider	*Petauroides volans*	•	•	V	V	
Squirrel Glider	*Petaurus norfolcensis*	•			E	L
Yellow-bellied Glider	*Petaurus australis*		•			
Leadbeater's Possum	*Gymnobelideus leadbeateri*	•	•	CE	E	L
Long-nosed Potoroo	*Potorous tridactylus*	•		V	NT	L
Long-footed Potoroo	*Potorous longipes*	•	•	E	V	L
Brush-tailed Rock Wallaby	*Petrogale penicillata*	•		V	CE	L
Grey-headed Flying-fox	*Pteropus poliocephalus*	•		V	V	L
Eastern Horseshoe Bat	*Rhinolopus megaphyllus*	•			V	L
Yellow-bellied Sheathtail Bat	*Saccolaimus flaviventris*	•			DD	L
Smoky Mouse	*Pseudomys fumeus*	•		E	E	L
Broad-toothed Rat	*Mastacomys fuscus*	•		V	E	L
Square-tailed Kite	*Lophoictinia isura*	•			V	L
White-bellied Sea-eagle	*Haliaeetus leucogaster*	•			V	L
Grey Goshawk	*Accipiter novaehollandiae*	•			V	L
Glossy Black-Cockatoo	*Calyptorhynchus lathami*	•	•		V	L
Swift Parrot	*Lathamus discolor*	•		CE	E	L
Turquoise Parrot	*Neophema pulchella*	•			NT	L
Powerful Owl	*Ninox strenua*	•	•		V	L
Barking Owl	*Ninox connivens*	•			E	L
Sooty Owl	*Tyto tenebricosa*	•	•		V	L
Masked Owl	*Tyto novaehollandiae*	•	•		E	L
Brown Treecreeper	*Climacteris picumnus victoriae*	•			NT	
Chestnut-rumped Heathwren	*Calamanthus pyrrhopygius*	•			V	L
Speckled Warbler	*Chthonicola sagittate*	•			V	L
Regent Honeyeater	*Anthochaera Phrygia*	•		CE	CE	L
Helmeted Honeyeater	*Lichenostomus melanops cassidix*	•		CE	CE	L
Hooded Robin	*Melanodryas cucullate*	•			BT	L
Giant Burrowing Frog	*Heleioporus australiacus*	•		V	V	L
Baw Baw Frog	*Philoria frosti*	•		E	CE	L
Brown Toadlet	*Pseudophryne bibronii*	•			E	L
Southern Toadlet	*Pseudophryne semimarmorata*	•			V	
Martin's Toadlet	*Uperoleia martini*	•			E	L
Green and Golden Bell Frog	*Litoria aurea*	•		V	V	L
Booroolong Tree Frog	*Litoria booroolongensis*	•		E	CE	L
Large Brown Tree Frog	*Litoria littlejohni*	•		V	E	L
Spotted Tree Frog	*Litoria spenceri*	•		E	E	L
Rosenberg's Goanna	*Varanus rosenbergi*	•			E	L
Lace Monitor	*Varanus varius*	•			E	
Eastern She-oak Skink	*Cyclodomorphus michaeli*	•			NT	L
Swamp Skink	*Egernia coventryi*	•			E	L
Alpine Bog Skink	*Pseudemoia cryodroma*	•			V	L

Flat-headed Galaxias	*Galaxias rostratus*	•		CE	V	I
Barred Galaxias	*Galaxias fuscus*	•		E	CE	L
Dwarf Galaxias	*Galaxiella pusilla*	•		V	E	L
Australian Grayling	*Prototroctes maraena*	•		V	V	L
Murray Cod	*Maccullochella peelii*	•		V	V	L
Trout Cod	*Maccullochella macquariensis*	•		E	CE	L
Macquarie Perch	*Macquaria australasica*	•		E	E	L
Empire Gudgeon	*Hypseleotris compressa*	•			V	L
Cox's Gudgeon	*Gobiomorphus coxii*	•			E	L
Orbost Spiny Cray	*Euastacus diversus*		•		E	L
Tall Astelia	*Astelia australiana*	•	•	V	V	L
Elegant Daisy	*Brachyscome salkiniae*	•	•		R	
Forest Sedge	*Carex alsophila*	•	•		R	
Blackfellow's Hemp	*Commersonia rossii*	•	•		V	
Gippsland Stringybark	*Eucalyptus mackintii*	•	•		R	
Gully Grevillea	*Grevillea barklyana*	•	•		V	L
Colquhoun Grevillea	*Grevillea celata*	•	•	V	V	L
Outcrop Guinea-flower	*Hibbertia hermanniifolia*	•	•		R	
Oval-leaf Grevillea	*Grevillea miqueliana*		•		P	
Brown Guinea-flower	*Hibbertia rufa*	•	•		R	
Toothed Leionema	*Leionema bilobum*	•	•		R	
Tree Geebung	*Persoonia arborea*	•	•		V	
Smooth Geebung	*Persoonia levis*	•	•		R	
Forest Geebung	*Persoonia sylvatica*	•	•		R	
Velvety Geebung	*Persoonia subvelutina*	•	•		R	
Forest Phebalium	*Phebalium squamulosum squamulosum*	•	•		R	
Tasmanian Wax-flower	*Philotheca virgata*	•	•		V	
Veined Pomaderris	*Pomaderris costata*	•	•		R	
Eastern Pomaderris	*Pomaderris discolor*	•	•		R	
Upright Pomaderris	*Pomaderris virgate*		•		V	
Serpent Heath	*Richea Victoriana*		•		R	
Leafless Pink-bells	*Leafless Pink-bells*	•	•		R	
Slender Fork-fern	*Tmesipteris elongate*		•		V	
Oval Fork-fern	*Tmesipteris ovata*	•			R	
Small Fork-fern	*Tmesipteris parva*	•			R	
Baw Baw Berry	*Wittsteinia vacciniacea*	•	•		R	
Sandfly Zieria	*Zieria smithii smithii*	•	•		R	

Key:

EPBC: National conservation status under the Commonwealth Environment Protection and Biodiversity Conservation Act 1999

CE = Critically Endangered
E = Endangered
V = Vulnerable

Vic Stat: Conservation status in Victoria

CE = Critically Endangered
E = Endangered
V = Vulnerable
R = Rare
DD = Data deficient
P = Parent (a species with all its subspecies listed as threatened: *Grevillea miqueliana cincta* is endangered, *G. m. miqueliana* and *G. m. moroka* are vulnerable).

FFG: L = listed as a threatened taxon under the Victorian *Flora and Fauna Guarantee Act 1988*.

Appendix S13. The area of forest and woodland EVC Groups (excl. wetlands) derived from EVC Group dataset (DSE 2005)

Description	Area (ha)	% of Total
Box Ironbark and lower fertility forests	359,598	3%
Coastal Scrub	47,814	0%
Dry Forest	2,704,455	26%
Heathland	293,356	3%
Heathy Woodland	329,216	3%
Herb Rich Woodland	170,834	2%
Lower Slope Woodlands	395,956	4%
Lowland Forests	598,168	6%
Mallee	1,541,988	15%
Montane Grasslands	389,979	4%
Plains Grasslands	240,562	2%
Plains Woodland	859,150	8%
Rainforests	36,856	0%
Riparian	275,426	3%
Riverine Grassy Woodland	395,956	4%
Rocky Outcrop	81,682	1%
Salt Tolerant Vegetation	93,137	1%
Sub-alpine Woodland	116,048	1%
Wet and Damp Forests	1,350,734	13%
Total	**10,280,915**	**100%**

Appendix S14. Tukey's HSD test for equal weight Zonation results between ACLUMP derived land use categories and areas allocated to logging. Bold text denotes statistically significance P<0.05.

Sequence	*diff*	*lwr*	*upr*	*p adj*
Informal Protected Area-Dedicated Reserve	**0.191**	**0.173**	**0.208**	**0.000**
Logging Permitted-Dedicated Reserve	**0.224**	**0.210**	**0.239**	**0.000**
Other Parks-Dedicated Reserve	-0.109	-0.232	0.015	0.122
Other State Forest-Dedicated Reserve	**-0.133**	**-0.161**	**-0.106**	**0.000**
Private Land-Dedicated Reserve	0.002	-0.014	0.019	0.998
Logging Permitted-Informal Protected Area	**0.034**	**0.014**	**0.053**	**0.000**
Other Parks-Informal Protected Area	**-0.299**	**-0.424**	**-0.175**	**0.000**
Other State Forest-Informal Protected Area	**-0.324**	**-0.355**	**-0.293**	**0.000**
Private Land-Informal Protected Area	**-0.188**	**-0.210**	**-0.167**	**0.000**
Other Parks-Logging Permitted	**-0.333**	**-0.457**	**-0.209**	**0.000**
Other State Forest-Logging Permitted	**-0.358**	**-0.387**	**-0.329**	**0.000**
Private Land-Logging Permitted	**-0.222**	**-0.241**	**-0.203**	**0.000**
Other State Forest-Other Parks	-0.025	-0.151	0.101	0.994
Private Land-Other Parks	0.111	-0.013	0.235	0.110
Private Land-Other State Forest	**0.136**	**0.105**	**0.166**	**0.000**

Appendix S15. Tukey's HSD test for linear weight Zonation results between ACLUMP derived land use categories and areas allocated to logging. Bold text denotes statistically significance $P<0.05$.

Sequence	*diff*	*lwr*	*upr*	*p adj*
Informal Protected Area-Dedicated Reserve	**0.186**	**0.169**	**0.204**	**0.000**
Logging Permitted-Dedicated Reserve	**0.213**	**0.199**	**0.227**	**0.000**
Other Parks-Dedicated Reserve	**-0.150**	**-0.272**	**-0.027**	**0.007**
Other State Forest-Dedicated Reserve	**-0.125**	**-0.153**	**-0.097**	**0.000**
Private Land-Dedicated Reserve	0.001	-0.016	0.017	1.000
Logging Permitted-Informal Protected Area	**0.027**	**0.007**	**0.046**	**0.001**
Other Parks-Informal Protected Area	**-0.336**	**-0.459**	**-0.212**	**0.000**
Other State Forest-Informal Protected Area	**-0.311**	**-0.342**	**-0.281**	**0.000**
Private Land-Informal Protected Area	**-0.185**	**-0.207**	**-0.164**	**0.000**
Other Parks-Logging Permitted	**-0.363**	**-0.486**	**-0.240**	**0.000**
Other State Forest-Logging Permitted	**-0.338**	**-0.367**	**-0.309**	**0.000**
Private Land-Logging Permitted	**-0.212**	**-0.231**	**-0.193**	**0.000**
Other State Forest-Other Parks	0.024	-0.101	0.150	0.994
Private Land-Other Parks	**0.150**	**0.027**	**0.274**	**0.007**
Private Land-Other State Forest	**0.126**	**0.096**	**0.156**	**0.000**

Appendix S16. Tukey's HSD test for log weight Zonation results between ACLUMP derived land use categories and areas allocated to logging. Bold text denotes statistically significance $P<0.05$.

Sequence	*diff*	*lwr*	*upr*	*p adj*
Informal Protected Area-Dedicated Reserve	**0.217**	**0.199**	**0.234**	**0.000**
Logging Permitted-Dedicated Reserve	**0.227**	**0.212**	**0.241**	**0.000**
Other Parks-Dedicated Reserve	**-0.208**	**-0.330**	**-0.086**	**0.000**
Other State Forest-Dedicated Reserve	**-0.151**	**-0.178**	**-0.123**	**0.000**
Private Land-Dedicated Reserve	-0.006	-0.023	0.010	0.897
Logging Permitted-Informal Protected Area	0.010	-0.009	0.030	0.661
Other Parks-Informal Protected Area	**-0.424**	**-0.547**	**-0.301**	**0.000**
Other State Forest-Informal Protected Area	**-0.367**	**-0.398**	**-0.337**	**0.000**
Private Land-Informal Protected Area	**-0.223**	**-0.244**	**-0.202**	**0.000**
Other Parks-Logging Permitted	**-0.434**	**-0.557**	**-0.312**	**0.000**
Other State Forest-Logging Permitted	**-0.378**	**-0.406**	**-0.349**	**0.000**
Private Land-Logging Permitted	**-0.233**	**-0.252**	**-0.214**	**0.000**
Other State Forest-Other Parks	0.057	-0.068	0.181	0.785
Private Land-Other Parks	**0.202**	**0.079**	**0.324**	**0.000**
Private Land-Other State Forest	**0.145**	**0.115**	**0.175**	**0.000**

Appendix S17. Tukey's HSD test for all weight Zonation results between areas previously clearfell logged post 1970, areas scheduled for clearfell logging under the 2019 Timber Release Plan and remaining forest area not logged. Bold text denotes statistically significance P<0.05.

Equal	*Sequence*	*Diff*	*Lower*	*Upper*	*P adj*
Wet and Damp Forest	**Previously Logged post 1970-Remaining EVC Group Areas**	**0.044**	**0.029**	**0.058**	**0.000**
Wet and Damp Forest	**TRP 2019- Remaining EVC Group Areas**	**0.057**	**0.030**	**0.083**	**0.000**
Wet and Damp Forest	TRP 2019-Previously Logged post 1970	0.013	-0.016	0.042	0.546
Dry Forest	**Previously Logged post 1970- Remaining EVC Group Areas**	**0.079**	**0.045**	**0.113**	**0.000**
Dry Forest	**TRP 2019- Remaining EVC Group Areas**	**0.108**	**0.034**	**0.182**	**0.002**
Dry Forest	TRP 2019-Previously Logged post 1970	0.029	-0.052	0.109	0.685
All Forests	**Previously Logged post 1970- Remaining EVC Group Areas**	**0.246**	**0.218**	**0.274**	**0.000**
All Forests	**TRP 2019- Remaining EVC Group Areas**	**0.256**	**0.199**	**0.312**	**0.000**
All Forests	TRP 2019-Previously Logged post 1970	0.010	-0.053	0.073	0.925
Linear	*Sequence*	*Diff*	*Lower*	*Upper*	*P adj*
Wet and Damp Forest	**Previously Logged post 1970-Remaining EVC Group Areas**	**0.035**	**0.021**	**0.049**	**0.000**
Wet and Damp Forest	**TRP 2019- Remaining EVC Group Areas**	**0.061**	**0.035**	**0.087**	**0.000**
Wet and Damp Forest	TRP 2019-Previously Logged post 1970	0.026	-0.003	0.054	0.094
Dry Forest	**Previously Logged post 1970- Remaining EVC Group Areas**	**0.049**	**0.019**	**0.079**	**0.000**
Dry Forest	**TRP 2019- Remaining EVC Group Areas**	**0.094**	**0.029**	**0.159**	**0.002**
Dry Forest	TRP 2019-Previously Logged post 1970	0.045	-0.026	0.117	0.294
All Forests	**Previously Logged post 1970- Remaining EVC Group Areas**	**0.221**	**0.193**	**0.249**	**0.000**
All Forests	**TRP 2019- Remaining EVC Group Areas**	**0.244**	**0.188**	**0.300**	**0.000**
All Forests	TRP 2019-Previously Logged post 1970	0.024	-0.038	0.086	0.646
Log	*Sequence*	*Diff*	*Lower*	*Upper*	*P adj*
Wet and Damp Forest	**Previously Logged post 1970-Remaining EVC Group Areas**	**0.020**	**0.008**	**0.031**	**0.000**
Wet and Damp Forest	**TRP 2019-Remaining EVC Group Areas**	**0.066**	**0.045**	**0.088**	**0.000**
Wet and Damp Forest	**TRP 2019-Previously Logged post 1970**	**0.047**	**0.023**	**0.070**	**0.000**
Dry Forest	**Previously Logged post 1970-Remaining EVC Group Areas**	**-0.048**	**-0.073**	**-0.023**	**0.000**
Dry Forest	TRP 2019-Remaining EVC Group Areas	0.035	-0.018	0.088	0.276
Dry Forest	**TRP 2019-Previously Logged post 1970**	**0.083**	**0.024**	**0.141**	**0.003**
All Forests	**Previously Logged post 1970-Remaining EVC Group Areas**	**0.184**	**0.156**	**0.212**	**0.000**
All Forests	**TRP 2019-Remaining EVC Group Areas**	**0.235**	**0.178**	**0.291**	**0.000**
All Forests	TRP 2019-Previously Logged post 1970	0.051	-0.012	0.114	0.141

Appendix S18. Area Analysis of the top scoring 10 percent for the equal, linear and log weight Zonation

Land Tenure	Area Equal Weight (ha)	% of Total Equal Weight	Area Linear Weight (ha)	% of Total Equal Weight	Area Log Weight (ha)	% of Total Equal Weight
Dedicated Reserves	907,329	44%	937,615	46%	865,018	42%
Informal Protection	275,295	13%	246,369	12%	286,977	14%
Logging Permitted	597,590	29%	500,841	24%	532,241	26%
Other Parks	1,208	0%	1,207	0%	968	0%
Other State Forests	42,119	2%	47,958	2%	20,761	1%
Private Land	244,341	12%	303,647	15%	318,545	16%
Other Land Use	17,024	1%	18,824	1%	12,051	1%
Total	**2,084,907**	**100%**	**2,056,460**	**100%**	**2,036,562**	**100%**