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

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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. In response, 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 have 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: disturbance, logging, protected areas, threatened species, wet eucalypt forests.

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 recognised, 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 the 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 characterised 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 & 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 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 modernise 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 data sets (1:2 000 000) and relative standard errors across agricultural land use (ABARES 2011). We cross-validated the ACLUMP data set 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 by 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° and streamside buffers, consisting mostly of 40 m (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

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%

tenure boundaries. We generated a Euclidean distance raster in ArcGIS with each internal 50x50 m 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 categorised 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: (i) General Management Zone (GMZ); (ii) Special Management Zone (SMZ); and (iii) historical reserves (DNRE 1998). General Management Zones are managed for a range of uses, but industrial logging is prioritised. Special Management Zones includes 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 data set 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) Groups (DELWP 2019d). The EVC Groups data set was developed by the Victorian Government to categorise 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 data set is a combination of a number of spatial data sets 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 Groups category, which covered 20 vegetation broad native vegetation types, including Wet and Damp Forests, Rainforests, Dry forests and Mallee EVC Groups. We applied this data set across all land tenures throughout Victoria.

Logging data

We used historical logging data sets and proposed logging planned under the 2019 Timber Release Plan (TRP) (VicForests 2019b), to analyse the EVC Groups targeted by commercial logging activities (DELWP 2019d). The logging history data set 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 1961–1962 season to the
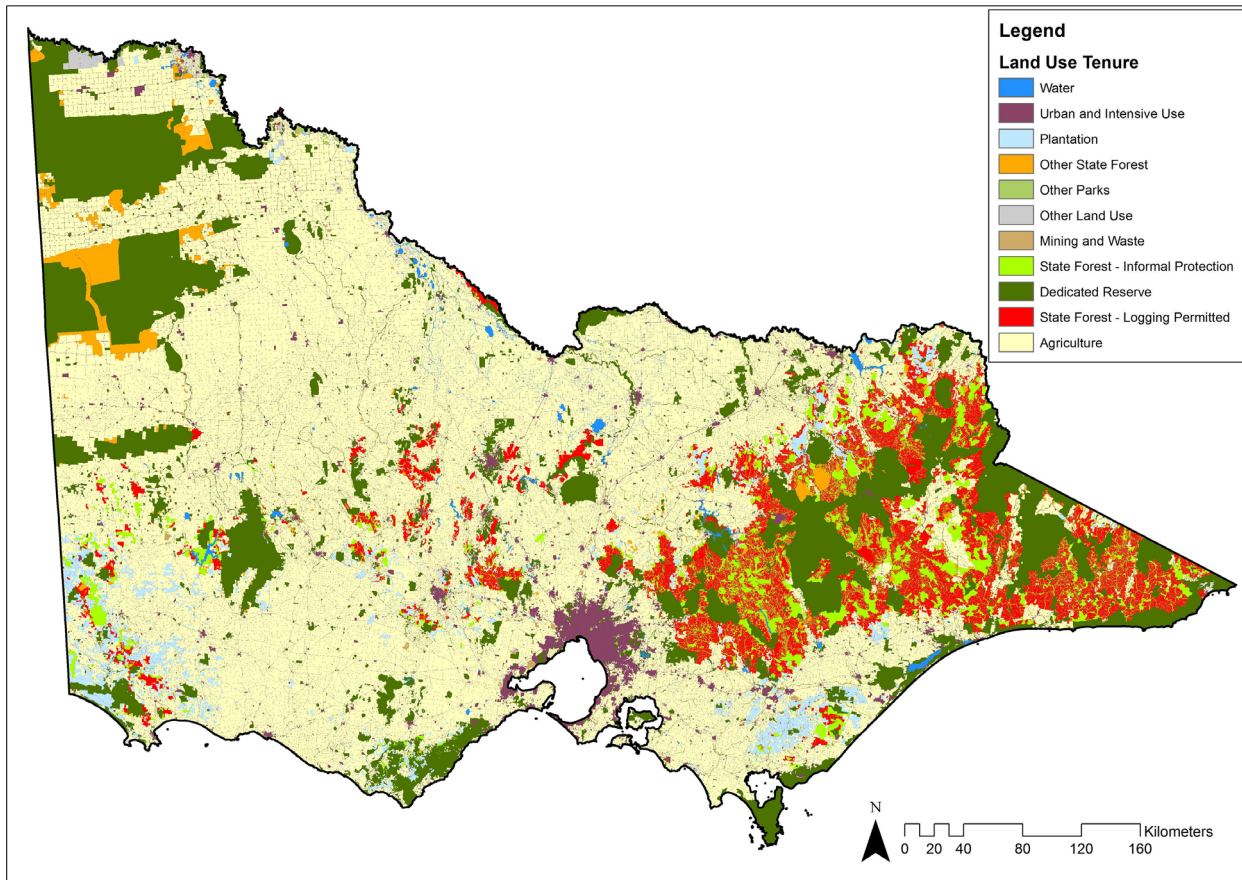
Fig. 1.   Land tenure and forest management zones across Victoria.

logging season 2016–2017. The TRP details the location and the gross area of planned logging, 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 Appendix S12). 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 75 × 75 m.

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 75 × 75 m cell across the landscape based on the following: (i) the relative suitability of a cell for each species; (ii) the weights assigned to species (see below); and (iii) 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.*
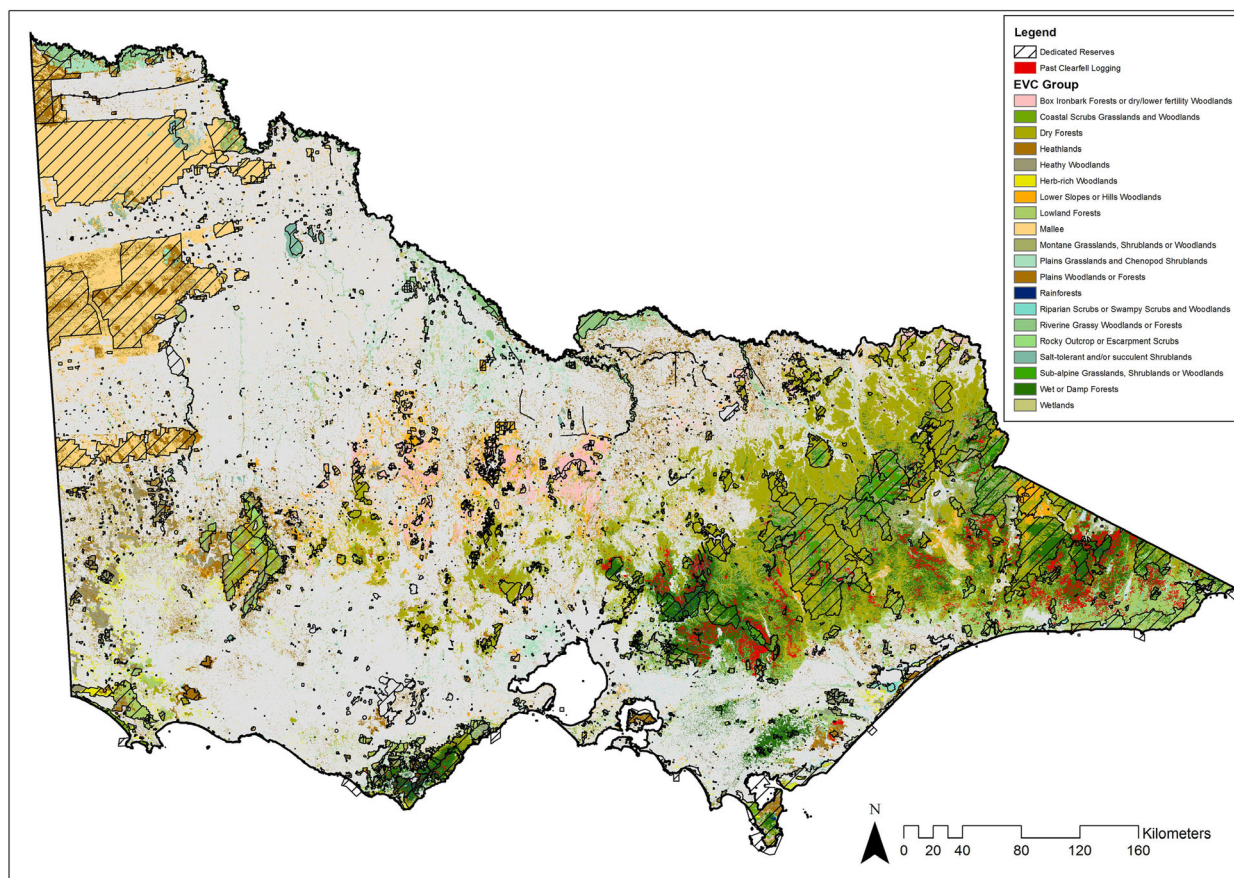
Fig. 2. Ecological Vegetation Class (EVC) Groups, conservation reserves and historic clearcutting.

2014). When a cell was removed, the value across remaining cells increased (Moilanen & Wintle 2006). Areas that contained habitat for rarer species were 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: (i) equal weight (the Zonation default), (ii) linear weight and (iii) log weight (Table 1) (Fiorella *et al.* 2010). The output for the Zonation analysis consisted of a raster grid data set with each cell across the landscape ranked from zero to one. The highest value 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 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
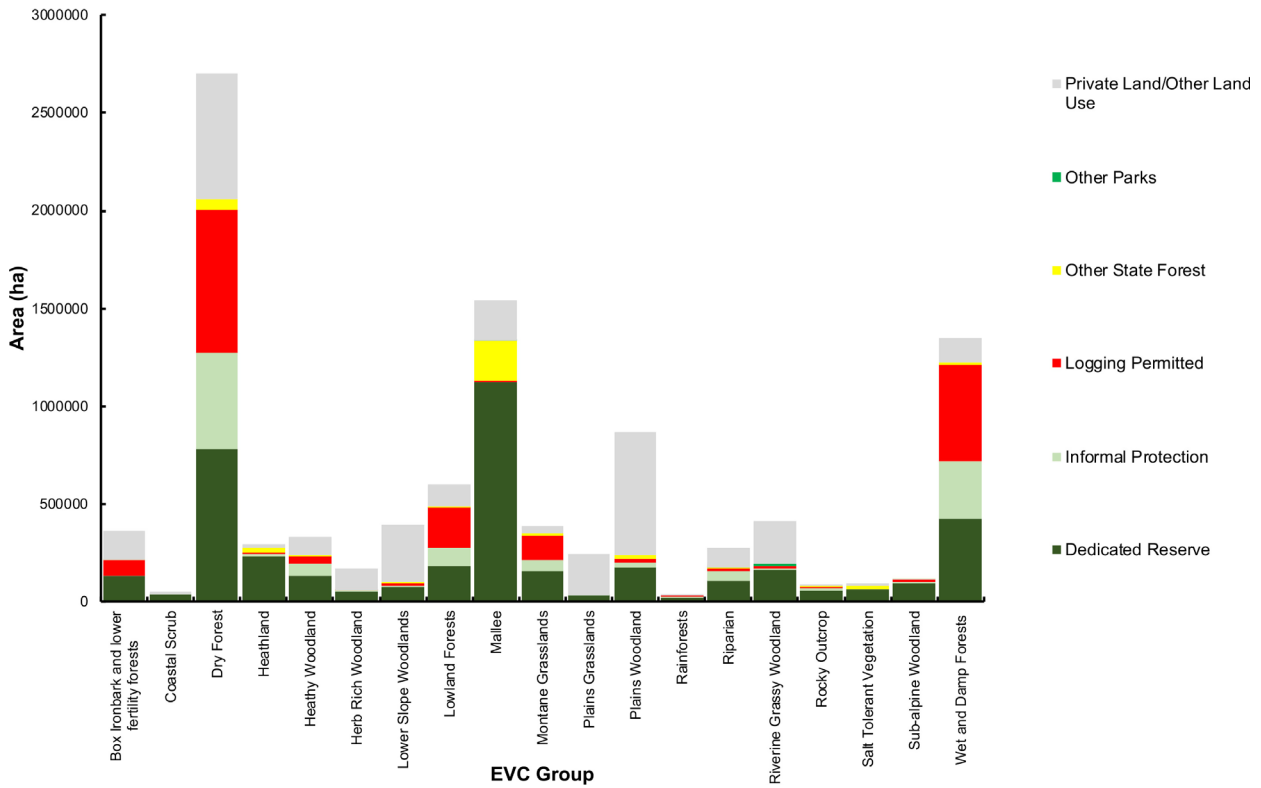
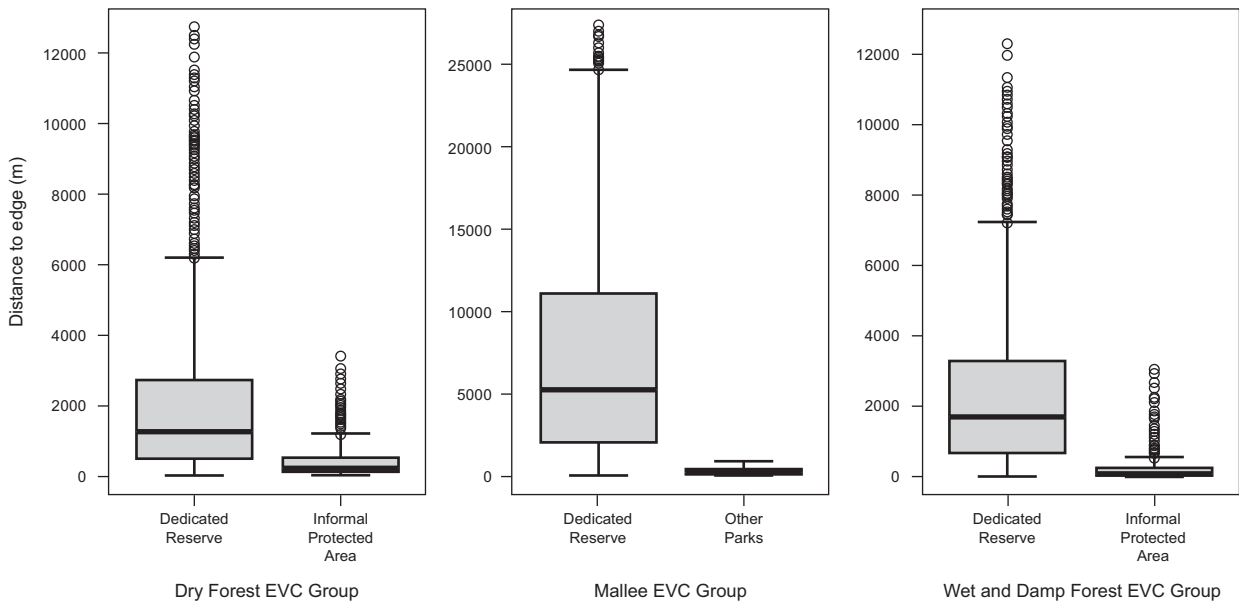**Fig. 3.** EVC Groups and land tenure classification by area.

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).

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

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	lower	Upper	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
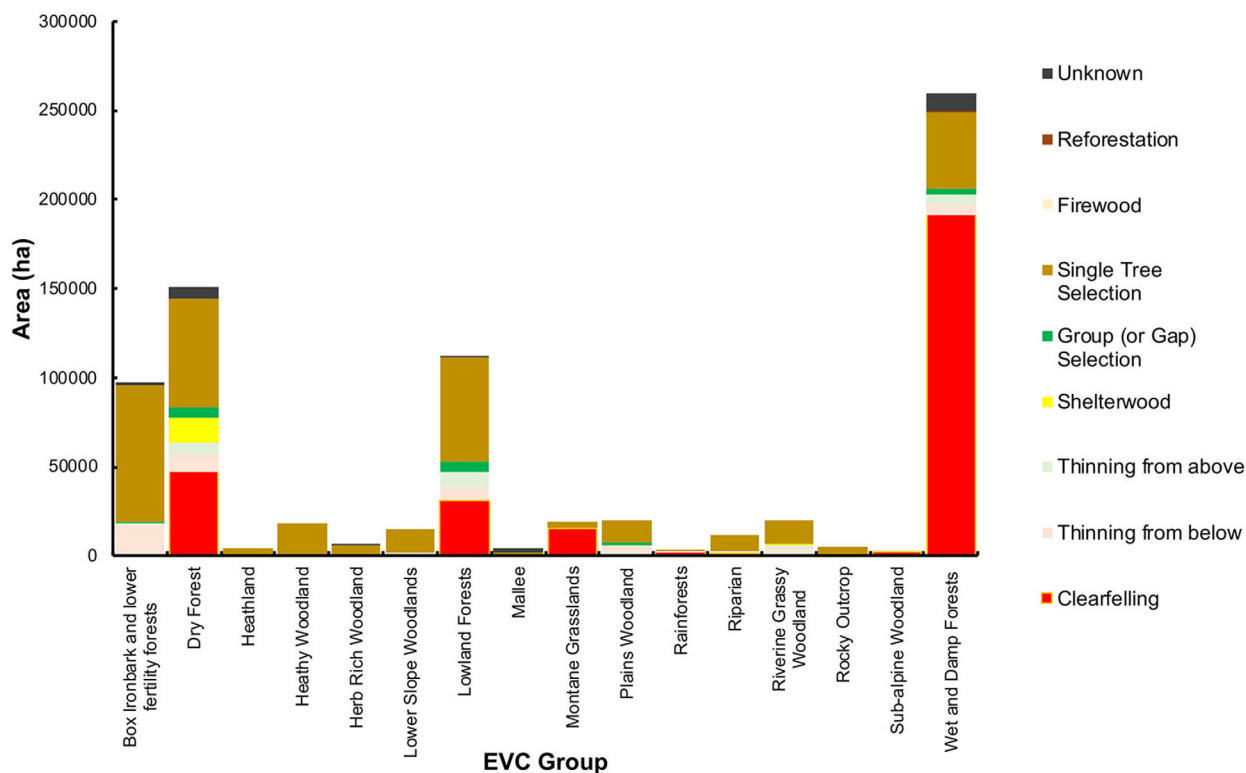
Fig. 5. Historic logging across the EVC Groups.

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 categorisation of the EVC Groups is 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 forests, equating to 59% of its total area. It has the largest percentage of its area allocated to state forests of all the EVC Groups.
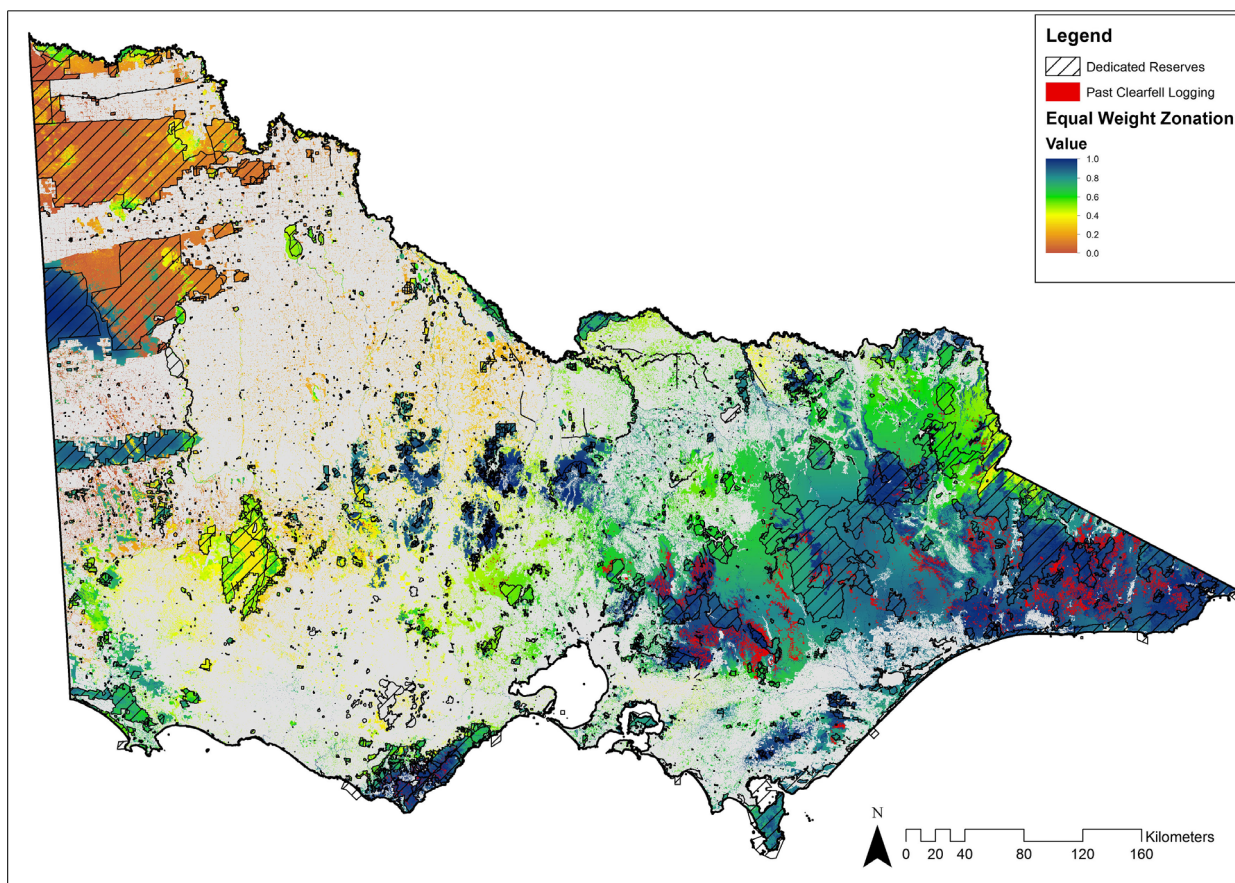
Fig. 6. Equal weight Zonation for forested areas with conservation reserves and historic logging overlaid.

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 1700 m. In comparison, the median distance to a boundary for informal protected areas was only 71 m. 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 1232 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 m. 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 5209 m.

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 1756 m. In comparison, the median distance to a boundary for informal protected areas was only 150 m. The *other park* tenure featured a median distance to its respective tenure boundary of 300 m (Appendix 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; Appendix S14). 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 4617 hectares or 0.3% of its area logged (Appendix S14).

Zonation habitat distribution prioritisation

Using Zonation analysis, we found the most important areas for forest-dependent threatened species which
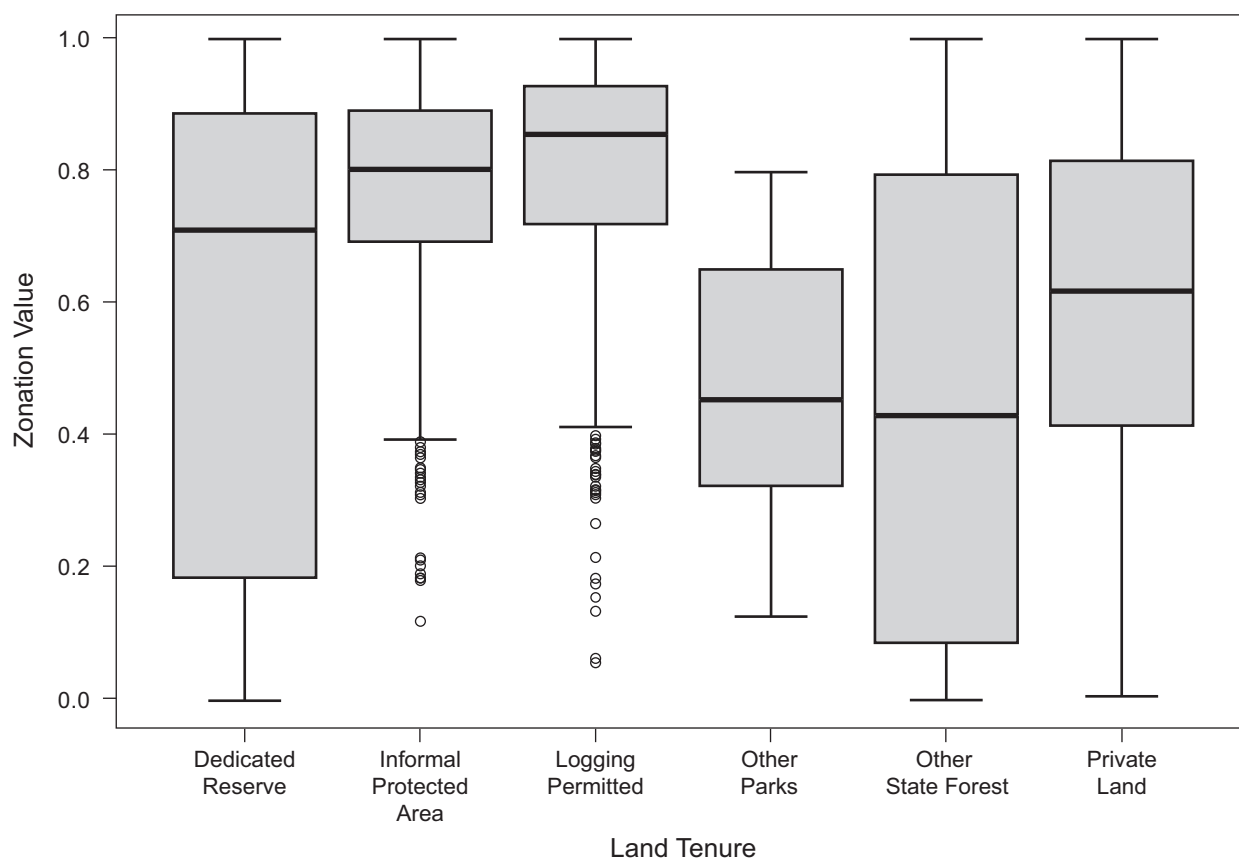
Fig. 7. Equal weight Zonation scores for selected land tenure across Victoria.

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 (Appendices 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 was the informal protected area, with a median Zonation values of 0.80, 0.79 and 0.84 for equal, linear and log weights, respectively (Appendices S4, S5 and S6). Dedicated reserves achieved median Zonation values of 0.71, 0.70 and 0.72 for equal, linear and log weights, respectively (Appendices 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 (Appendices 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, Appendices S15 and S16).

The Wet and Damp Forest EVC Group featured one of the highest median Zonation equal weight scores in our analysis of 0.90 (Appendices 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 linear and log weights (Appendices 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 (Table 5 and Appendix S17). 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 weight 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

Table 4. Tukey's HSD test for equal weight Zonation results between land tenures and forest management zones. Statistical significance $P < 0.05$

Land tenure comparison	Diff	Lower	Upper	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**

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 clear-cut and unlogged areas, 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 m 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, 1988). Collectively, these findings indicate that high productivity areas for tree growth
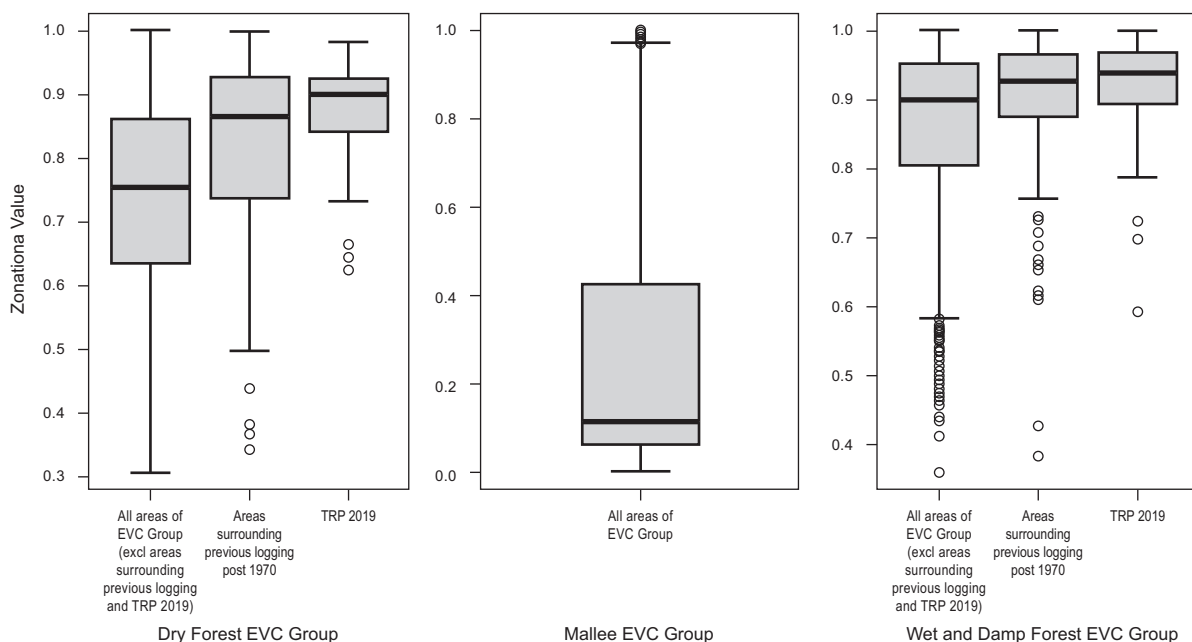
Fig. 8. Equal Weight Zonation prioritisation scores for selected EVC Groups.

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 have 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 modernise 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 modernising 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

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. 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 EVC Groups	**Remaining area of EVC Group/previously logged**	**0.246**	**0.218**	**0.274**	**0.000**
All Forest EVC Groups	**Remaining area of EVC Group/TRP 2019**	**0.256**	**0.199**	**0.312**	**0.000**
All Forest EVC Groups	Previously logged/TRP 2019	0.010	−0.053	0.073	0.925

available to logging (Appendix S18). 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.

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SUPPORTING INFORMATION

Additional supporting information may/can be found online in the supporting information tab for this article.

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