Forest Ecology and Management 490 (2021) 119122

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Can chainsaw carved hollows provide an effective solution to the loss of natural tree cavities for arboreal mammals?

William Terry[a,*], Ross L. Goldingay[a], Rodney van der Ree[b]

[a] Faculty of Science & Engineering, Southern Cross University, Military Road, East Lismore, NSW 2480, Australia
[b] WSP, 28 Freshwater Place, Southbank, Victoria 3006, Australia

A R T I C L E I N F O

Keywords:
Chainsaw hollow
Nest box
Mammal
Tree hollow
Multi-method occupancy
Tree cavity insert

A B S T R A C T

Constructing hollows or cavities in trees with chainsaws is an emerging approach to manage hollow-dependent species in hollow depleted landscapes. Small-scale experiments are required to refine this approach before implementing on a broad scale. We addressed two questions: i) are chainsaw hollows used by the regionally threatened brush-tailed phascogale (*Phascogale tapoatafa)* and the non-threatened sugar glider *(Petaurus notatus)*, ii) do chainsaw hollows retain their integrity over time. We paired 45 chainsaw hollows with nest boxes of equivalent internal dimensions in southeastern Australia and inspected these on 20 occasions over 2.5 years. Camera traps revealed phascogales visited some cavities within hours of installation and monthly inspections revealed rapid uptake of these hollows by both target species. Overall, phascogales and sugar gliders used 32% and 84% of the chainsaw hollows respectively, and 21% and 82% of the nest boxes. We used multi-method occupancy to compare detection within the two types of cavities. Detection models that included cavity type had more support than those without. Detection of both species was substantially higher in the chainsaw hollows compared to the nest boxes. Over the 2.5-year monitoring period the faceplates of some chainsaw hollows showed signs of deformity. Callous regrowth over the faceplate was pronounced on some trees suggesting the need for periodic maintenance. Our study confirms the potential of chainsaw hollows to restore habitat for hollow-dependent mammals but highlights periodic maintenance is likely to be a feature of this approach as it is with nest boxes.

1. Introduction

Globally, 33% of the world's extant forests have been converted from mature to young (<140 years of age) as a result of land use changes, timber harvesting, insect attack, wind-throw and change in wildfire regimes (McDowell et al., 2020). The loss of natural cavities (hollows) in modified forests in particular, is an international conservation issue (Kikuchi et al., 2013; Edworthy and Martin, 2013; Lindenmayer et al., 2014; Le Roux et al., 2016) with serious consequences for hollow-dependent wildlife (Gibbons et al., 2000; Cockle et al., 2011; Goldingay, 2011; Kikuchi et al., 2013; Mine et al., 2014; Flesh, 2019). In Australia, approximately 300 species of vertebrates use tree hollows (Gibbons et al., 2002) for shelter, protection from predators, and raising young (Bennett et al., 1994; van der Ree et al., 2006; Goldingay, 2009, 2011).

Woodpeckers create cavities in many parts of the world, but not all of these are suitable for other animals (Cockle et al., 2011). However, in Australia and New Zealand, woodpeckers are absent and hollow formation relies on the slow process of decay which usually starts with a scar inflicted on the tree as a result of damage or loss of limbs (Gibbons et al., 2000; Adkins, 2006). Deep hollows required by large species can take several hundred years to develop (Koch et al., 2008; Le Roux et al., 2016; Gibbons et al., 2000). The reduction in hollow-bearing trees is recognized as a serious threat to the survival of many mammals (Gibbons et al., 2002; Lindenmayer et al., 2014).

Methods to accelerate the development of natural hollows have included the use of explosives, poisons, introduction of fungi, girdling, topping by chainsaw and ring barking (Gibbons et al., 2000). In recent decades, nest boxes have become a widespread tool for land managers where natural hollows are in short supply. Nest boxes have potential to assist in the conservation of threatened hollow-dependent species (Morris et al., 1990; Harley, 2006; Mine et al., 2014; Beyer and Goldingay, 2006; Goldingay and Stevens, 2009; Durant et al., 2009) but they are likely to only be an interim measure due to attrition (Lindenmayer

* Corresponding author.
E-mail address: wterry@outlook.com.au (W. Terry).

https://doi.org/10.1016/j.foreco.2021.119122
Received 28 January 2021; Received in revised form 26 February 2021; Accepted 27 February 2021
Available online 20 March 2021

et al., 2009).

Despite nest boxes being effective tools for monitoring and potentially offsetting habitat loss, there are several drawbacks. Nest boxes have variable lifespans which may be influenced by local rainfall, the method of attachment to trees and the types of materials selected for construction, though some may still function after 20 years (Goldingay et al., 2018). Some studies have raised concerns that nest boxes may not provide protection from temperature extremes compared to natural cavities (Rowland et al., 2017; Griffiths et al., 2018), though there is little direct evidence that this poses a fitness cost (Goldingay, 2017; Saunders et al., 2020). The use of chainsaw constructed hollows (Carey and Gill, 1983; Carrie et al. 1998; Wood et al., 2000; Saenz et al., 2001; Carey, 2002) has recently received renewed attention as an alternative to nest boxes (Rueegger, 2017; Griffiths et al., 2018). While results are promising for providing an alternative to nest boxes, there are many questions that need to be investigated before chainsaw hollows are routinely adopted in habitat restoration.

We installed chainsaw hollows to address two questions i) are chainsaw hollows used by the regionally threatened brush-tailed phascogale (*Phascogale tapoatafa)* and the non-threatened sugar glider *(Petaurus notatus)*, and ii) do chainsaw hollows retain their integrity over time. Phascogales readily make use of nest boxes (Soderquist et al., 1996; Rhind and Bradley, 2002; Goldingay et al., 2018, 2020a) so we installed chainsaw hollows and nest boxes in pairs, with the latter serving as a reference to measure the relative success of the chainsaw hollows. We also investigated changes to these cavities over a 2.5-year period to determine whether maintenance is required for these cavities to remain functional.

2. Methods

2.1. Study species

The brush-tailed phascogale (*Phascogale tapoatafa*) (Fig. 1a.) is a regionally threatened species (IUCN 2019), with long-term monitoring suggesting it is in decline (Holland et al., 2012). One of the factors that has threatened this species has been the historic loss of hollows in its preferred habitat (Victorian State Government, 2003). The phascogale appears to require many hollows to complete its lifecycle (van der Ree et al., 2006). Therefore, an important element of a conservation program for this species will be to increase the availability of tree hollows through extensive areas of degraded habitat. Another hollow-dependent mammal, the sugar glider (*Petaurus notatus*) (Fig. 1b), is sympatric with the phascogale.

2.2. Study area

Eight study locations (Fig. 2) were selected from two physiographic provinces at altitudes between 400 and 600 m above sea level. Three sites were in eucalypt woodlands with poorly drained, fertile granitic and sedimentary soils. The remaining five study sites were in box-ironbark eucalypt forests with infertile soils derived from a range of geologies (Victorian State Government, 2020). Average annual rainfall is between 500 mm and 800 mm (Bureau of Meteorology, 2021). Trees rarely exceeded 25 m and all study sites showed evidence of intensive timber harvesting from early European settlement. All sites were connected to larger patches of habitat (>100 ha). These locations all supported known populations of brush-tailed phascogales and sugar gliders. The two cavity types (chainsaw hollow, nest box) were installed in pairs with 20–30 m between the cavities. There were 45 pairs established across the 8 locations with 2–9 pairs per location.

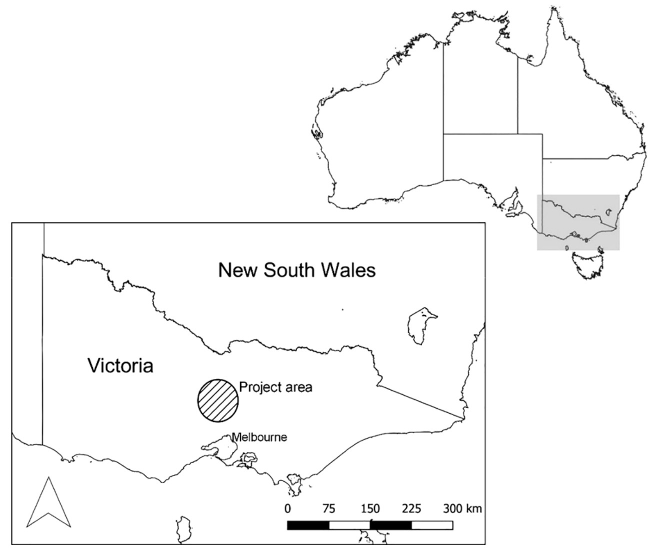

Fig. 2. Map of project area in central Victoria, Australia.

2.3. Tree selection

To minimise the risk of tree failure due to the installation of carved hollows or nest boxes, we selected live stems that would still retain two thirds of their thickness following construction of a chainsaw hollow (Mattheck et al., 1994). Only rough barked eucalypts were used in this study because they are preferred feeding trees for phascogales (Traill and Coates, 1993; Scarff et al., 1998).

2.4. Artificial cavity construction

A total of 45 cavities were constructed using chainsaws. Thirty-seven were installed in January 2018 with a prefabricated timber faceplate

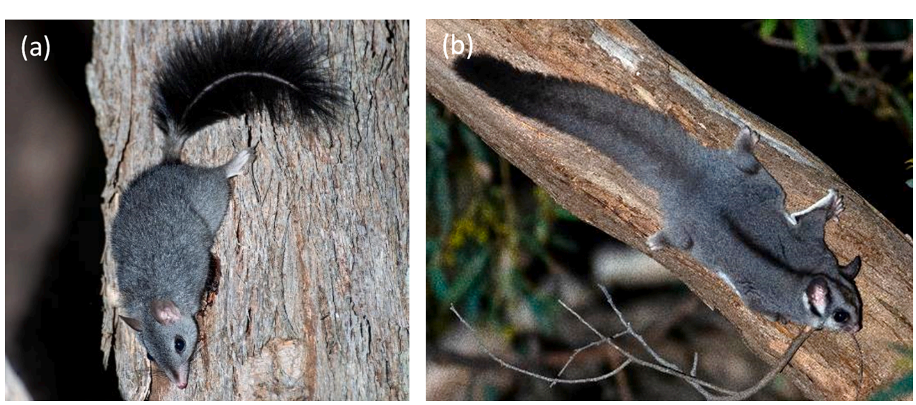

Fig. 1. (a) Brush-tailed phascogales and (b) sugar gliders were targeted in this project.

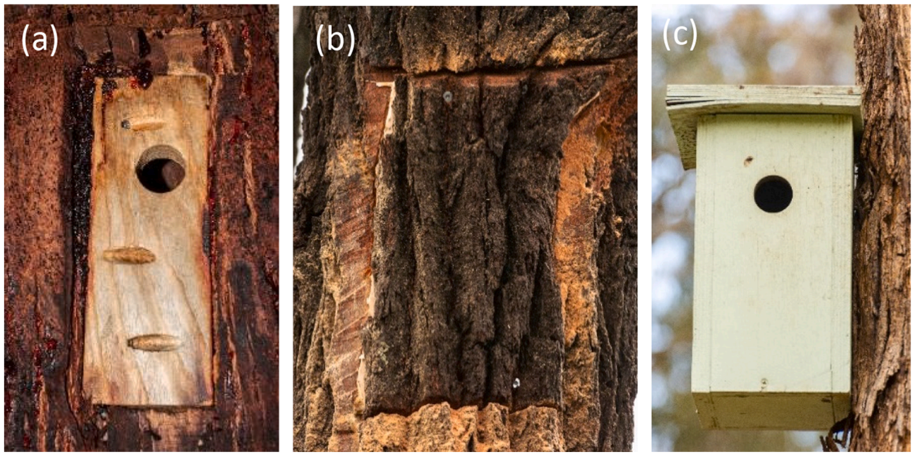

Fig. 3. The initial chainsaw hollows (a) had a design with a prefabricated faceplate constructed from dried hardwood. The later chainsaw hollows (b) had a piece of the tree removed during construction which was used as the faceplate. Nest boxes (c) of the same internal dimensions were installed on nearby trees for both designs.

(Fig. 3a). The internal dimensions were 27 cm in height, 16 cm deep and 12 cm wide (i.e. 5,184 cm^3 in volume). Another nine cavities were installed in June 2018. These hollows measured 40 cm high, 16 cm deep and 12 cm wide (i.e. 7,680 cm^3 in volume). A faceplate was made from the front surface removed from the tree and was screwed over the front of these later carved hollows (Fig. 3b). The greater vertical dimension in the second lot of hollows was to allow for the accumulation of nesting material from phascogales.

Nest boxes were constructed from 1.8 cm thick marine ply and painted with water based non-toxic exterior paint (Fig. 3c). A light green colour with a white base paint was used to increase reflectance and minimise heating of the nest boxes during summer (see Griffiths et al., 2017). Nest boxes were installed by hanging on a single galvanized nail six weeks after chainsaw hollows were installed. Both chainsaw hollows and nest boxes faced south-east to minimise extreme temperature fluctuations in summer (Goldingay, 2015), had an entrance hole of 4 cm and were installed at a height of 3–4 m above ground. Chainsaw hollow and nest box pairs were constructed to the same internal dimensions.

2.5. Cavity surveys

Monitoring of cavities began in March 2018 and was conducted monthly for the first year, bimonthly in the second year and then twice in the final six months. A ground operated inspection camera (BrightStar, Melbourne) was used to check inside each cavity without disturbing any wildlife. The species, total number of animals, or presence of nesting material or scats were recorded.

Infrared flash camera traps (Reconyx Hyperfire 2 HF2X) were installed on three chainsaw hollows at two different locations immediately following construction to determine the interval before they were discovered by hollow-using species. Each camera was set to take five still images with no interval between each trigger over a combined total of 289 camera trap days.

2.6. Habitat variables

The tree species and diameter at breast height (DBH) were recorded for each tree used. Habitat data were collected within a 10 m radius circle around each tree that contained a cavity (chainsaw hollows and nest boxes). In each circle we recorded the area of fallen timber (m^2) which would potentially be used in foraging by phascogales (Lunt, 1988), number of hollows (entrance of $<$ 7 cm), and the number, species and diameter of all stems (>5cm DBH) and number of dead trees (stags).

2.7. Data analysis

We employed the multi-method occupancy approach of Nichols et al. (2008) as implemented in program PRESENCE version 12.24 (USGS Patuxent Wildlife Research Centre, Laurel, MD, 20708, USA) to analyse our results. This approach uses repeat observations at sites containing two or more detection methods to estimate method-specific detection as well as occupancy across all sites and occupancy at the individual site scale (i.e. small-scale occupancy). Our two cavity types are analogous to different methods of detection at each site. We tested whether a model that estimated detection in each cavity type separately fit the data better than one that didn't (i.e. a null model). Both species undergo seasonal breeding and variation in local abundance (Suckling, 1984; Soderquist, 1993b) which may influence detection. Both species are known to be influenced by variation in habitat (e.g. Suckling, 1984; Mansfield et al., 2017; Goldingay et al., 2020a). Therefore, we also constructed models in which detection could vary seasonally or be influenced by habitat covariates. Models were ranked in PRESENCE by Akaike's Information Criterion (AIC), from the lowest to the highest AIC value. We used the small sample size correction represented by AICc (Burnham and Anderson 2004). The plausibility of competing models is indicated by their difference (Δ) in AICc from the top model. Any models within 2ΔAICc of the top model are considered equally plausible to explain the data (Burnham and Anderson, 2004). Models with values of $\Delta AIC > 4$ suggest a poorer fit to the data. The relative support for a model is also indicated by its model weight (*w*).

We constructed detection histories for the phascogale and the sugar glider reflecting whether each was detected (1) or not (0) by each pair of cavities across sample occasions (e.g. $H = 00\ 01\ 10\ 11\ldots$). For the sugar glider we relied exclusively on whether individuals were seen in a cavity during each occasion. For the phascogale, which may use a large number of cavities and range more widely (Soderquist, 1995; van der Ree et al., 2006), we used observations of animals as well as whether a nest was present and showed evidence of use since the previous survey (e.g. new nesting material including bark strips, foliage, bird feathers and new scats). Because the cavities were not installed concurrently, we excluded the first three months of checks of the carved hollows to allow for a period of discovery and habituation. This left us with 17 sample occasions encompassing all four seasons of the year. Both species show seasonal changes in breeding activity which influences their use of hollows. Therefore, as part of our modelling we investigated whether a model that included a seasonal influence on detection fit the data better than a model where detection was constant over occasions or completely time varying. Preliminary modelling showed the small-scale occupancy parameter theta was estimated close to 1 for the phascogale so we fixed this to 1 in all subsequent modelling to ensure model convergence.

Our focus was on factors that influence detection in our cavities. Therefore, the habitat variables we collected around each host tree were included as detection covariates in our models. There were seven tree species in the sample but we predicted that the red ironbark (*Eucalyptus sideroxylon*), may influence cavity use so we included a covariate to contrast this species against all others. The covariates we investigated were the number of hollows, the number of stags and the number of tree stems.

2.8. Change in cavity condition

Each cavity was checked in July 2020, photographed and callous (wound) growth measured with a tape measure to nearest centimetre. The condition of each nest box was also recorded. The build-up of moisture within each cavity was assessed and scored from 0 (no moisture) to 3 (high levels of visible moisture with wet substrates). The pole mounted inspection camera did not allow for depth of any standing water to be measured.

3. Results

3.1. Visitation to cavities

Brush-tailed phascogales (n = 74 animal and nest detections) and sugar gliders (n = 632) were the most frequently encountered species utilizing the cavities (Fig. 4.a-c) accounting for 96% of cavity detections (nests, scats and animals present) with the pole mounted camera. Phascogales and sugar gliders used 32% and 84% of the chainsaw hollows respectively, and 21% and 82% of the nest boxes. A brush-tailed phascogale was detected by camera trap inspecting the exterior of the chainsaw hollow at 0204 h on the first evening after installation. A sugar glider was photographed entering a cavity four days after installation. Phascogale maternal nests were recorded inside four chainsaw hollows during the 2.5 year monitoring period.

Two other small mammals were recorded showing interest in the hollows. These included the yellow-footed antechinus (*Antechinus flavipes*), a small dasyurid, which was detected in one chainsaw hollow at two sites and a feather-tailed glider (*Acrobates pygmaeus*), photographed on a camera trap inspecting one chainsaw hollow.

A month after installation, two chainsaw hollows had termites present and one was filled entirely rendering it unusable by our target species. This hollow and its accompanying nest box were therefore excluded from the analysis. Also recorded after one month was Fungi (taxa unknown) in one chainsaw hollow at two sites.

3.2. Detection of target species in chainsaw hollows and nest boxes

3.2.1. Phascogale

A model that included cavity type as an influence on detection had more support than one without. Models that included season and tree species (red ironbark vs other) also had strong support. Including these two covariates with detection method (cavity type) produced a model with strong support in the data with a model weight of 0.97 (Table 1). A model that included a fully time-varying influence on detection had no support in the data, differing to the detection method model by 28 AICc units. The inclusion of other covariates such as local abundance of hollows, stags, or tree stems, showed no improvement in model fit to the detection method model. Detection of phascogales was higher in the chainsaw hollows compared to the nest boxes. Detection was higher in summer and autumn (Fig. 5a) compared to winter and spring, and was approximately twice as high on ironbark compared to other tree species (Fig. 5b). Large-scale occupancy was estimated at 0.46 ± 0.08 by the top model.

Table 1
Model selection results for the top four models for cavity use in Central Victoria during 2018–2020. Theta was fixed at 1 for the phascogale. Cavity = two cavity types.

Model	AICc	ΔAICc	*w*	ML	*k*
Phascogale					
psi(.), p(cavity + seasons + ironbark)	463.47	0.00	0.97	1.00	8
psi(.), p(cavity + seasons)	470.41	6.94	0.03	0.03	7
psi(.), p(cavity + ironbark)	474.94	11.47	0.00	0.00	5
psi(.), p(cavity)	482.24	18.77	0.00	0.00	4
Sugar glider					
psi(.), theta(.), p(cavity + DBH)	731.64	0.00	1.00	1.00	5
psi(.), theta(.), p(cavity)	744.45	12.81	0.00	0.00	4
psi(.), theta(.), p(cavity + seasons)	748.74	17.10	0.00	0.00	7
psi(.), theta(.), p(.)	757.48	25.84	0.00	0.00	3

3.2.2. Sugar glider

A model that included cavity type as an influence on detection had much more support than one without. A model that included DBH of the cavity tree, along with cavity type had the most support in the data with a model weight of 1.0 (Table 1). A model that included a fully time-varying influence on detection had no support in the data, differing to the detection method model by > 40 AICc units. The inclusion of covariates such as local abundance of hollows, stags, or tree stems, showed no improvement in model fit to one with cavity type only. Detection of sugar gliders was substantially higher in the chainsaw hollows (0.22 ± 0.08) compared to the nest boxes (0.06 ± 0.02), when DBH of the cavity tree is held at its mean. Tree size had a strong negative influence on detection with higher though more variable values at smaller tree sizes (Fig. 6). Large-scale occupancy and small-scale occupancy for the top model were estimated at 0.78 ± 0.07 and 0.66 ± 0.23, respectively.

3.3. Changes in cavity condition

Chainsaw hollows were subject to callous regrowth of bark around and over the faceplate, and a build-up of moisture or vulnerability to water ingress. At the final inspection 70.5% of chainsaw hollows compared to only 13.6% of nest boxes had a build-up of moisture (>1 moisture index). Of these chainsaw hollows, 29.5% had moderate to high (>2 moisture index) rates of moisture (Fig. 7a). The contents of three chainsaw hollows was so wet that old nesting material had turned into mud-like material. One check of cavities was undertaken during

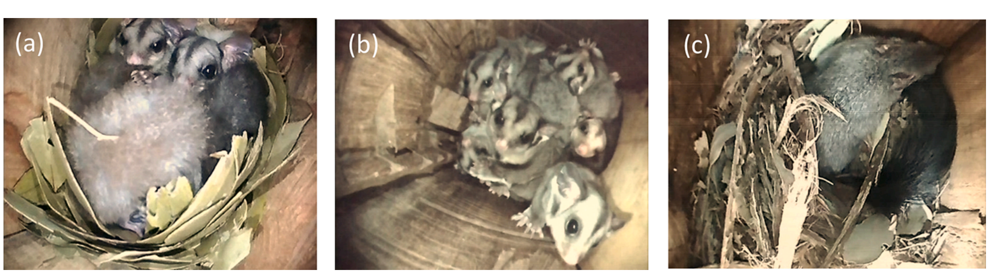

Fig. 4. Images taken by a pole mounted camera inside chainsaw hollow cavities. (a-b) sugar gliders, (c) a phascogale in a characteristic nest of stripped stringybark.

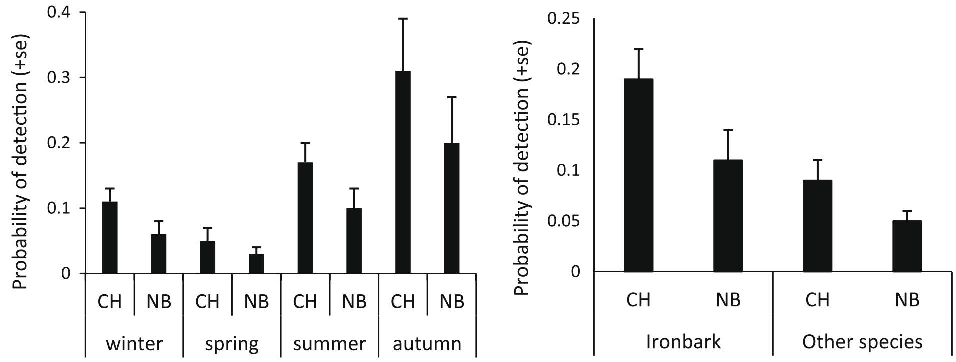

Fig. 5. (a) Probability of detection of phascogales in chainsaw hollows (CH) and nest boxes (NB) over the various seasons in Central Victoria during 2018–2020. (b) The influence of cavity type with ironbark versus other tree species when detecting phascogales.

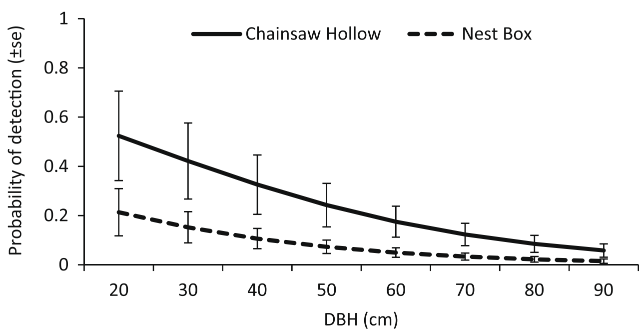

Fig. 6. The influence of cavity type, and tree DBH on the probability of detection of the sugar glider in Central Victoria during 2018–2020.

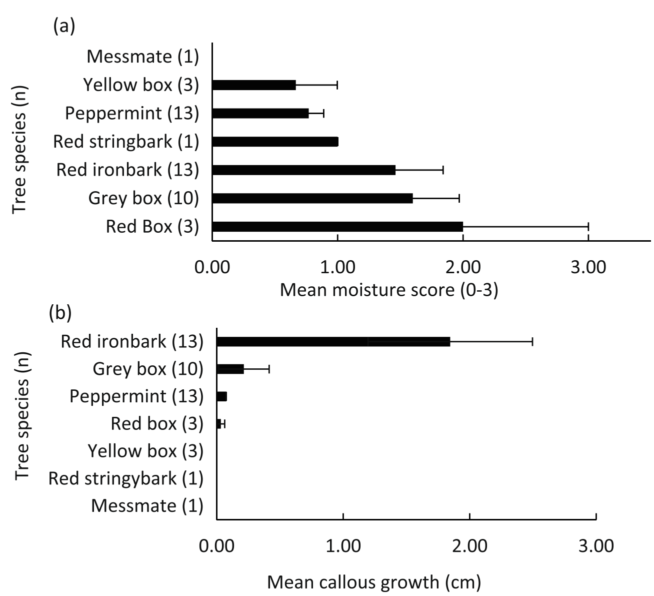

Fig. 7. Mean (±SE) score of moisture (a) inside chainsaw hollows and mean callous growth (b) recorded for each tree species. n indicates the number of hollows per tree species. Tree species include messmate (*Eucalyptus obliqua*), yellow box (*E. melliodora*), narrow-leaf peppermint (*E. radiata*), red stringybark (*E. macrorhyncha*), red ironbark (*E. sideroxylon*), grey box (*E. microcarpa*) and red box (*E. polyanthemos*).

rainfall and water was observed trickling down the insides of faceplates on the pole mounted inspection camera.

Callous regrowth speed varied among tree species (Fig. 7b) with red ironbark (Fig. 8a) displaying the greatest degree of callousing. Grey box eucalypts showed signs of the tree swelling above and below the chainsaw hollows (Fig. 8b). Three of the nine larger chainsaw hollows with natural faceplates had begun to warp open leaving large gaps of up to 3 cm (Fig. 8c). Some nest boxes also declined in condition with 22.7% having lids that were beginning to warp from moisture.

4. Discussion

4.1. Detection of target species in chainsaw hollows and nest boxes

Both target species were detected at higher frequencies in the chainsaw hollows compared to the nest boxes. The higher detection rate in chainsaw cavities compared to nest boxes by the brush-tailed phascogale suggests the installation of chainsaw hollows could be an important method for restoring habitat quality for this threatened species. Maternal nests of phascogales were recorded in four chainsaw hollows but none in nest boxes suggesting these cavities satisfied breeding requirements which are likely to be greater than shelter only requirements (see Soderquist, 1993a).

Phascogales showed a pronounced seasonal variation in detection in cavities with higher values recorded in summer and autumn. The higher values during these seasons are likely to reflect the dispersal of individuals away from the natal nest (Soderquist and Lill, 1995). The strong seasonal variation in detection suggests that the timing of surveys will be critical to measure the success of artificial cavities in future studies for phascogales. Phascogales were also influenced by whether the host tree was an ironbark or not. This may reflect the coarser bark on this tree which provides a better substrate for rapid transit to and from the den. Detection of sugar gliders declined with increasing host tree size which may reflect larger trees being more likely to offer alternative natural denning sites.

Previous studies using nest boxes report frequent use by both of our target species (Goldingay et al., 2020a,b; Soderquist et al., 1996). This suggests the greater rate of detection in the chainsaw hollows compared to nest boxes reflects a preference for the former. Sugar gliders were the most frequent users of the chainsaw hollows which may reflect smaller home ranges (3–6 ha; Suckling, 1984; Quin et al., 1992) compared to those of phascogales (30–50 ha; Soderquist, 1995; van der Ree et al., 2001; Rhind, 2003). The apparent preference for chainsaw hollows over nest boxes may be due to chainsaw hollows providing a more stable and lower thermal environment compared to nest boxes (Griffiths et al., 2018). Chainsaw hollows may also better mimic the physical appearance of a natural hollow and allowed easy access and less exposure to predators than nest boxes.

The installation of our pairs of chainsaw hollows and nest boxes were not designed to identify the optimal number of hollows to install in a cluster. A study at a separate location within our broader study region had high rates of use by our target species when nest boxes were installed in clusters of three and 700 m between clusters (Goldingay

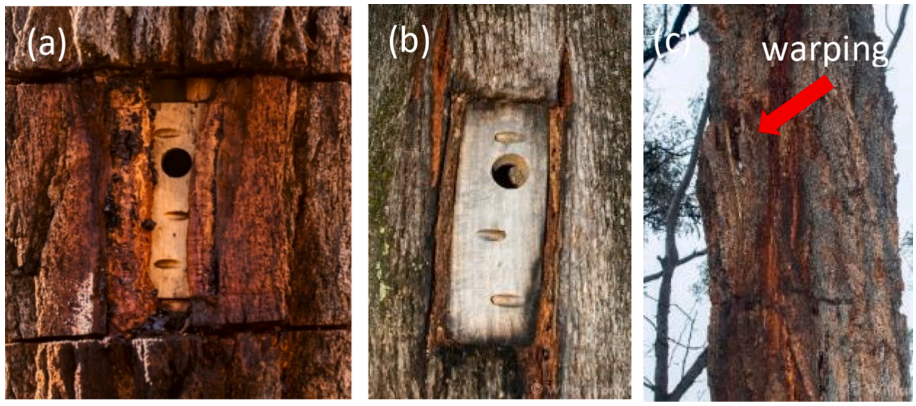

Fig. 8. Example of callous regrowth over the faceplate on an ironbark eucalypt (a). Grey box (b) were prone to swelling above and below chainsaw hollows. Three natural faceplates (c) warped open leaving gaps of up to 3 cm.

et al. 2020a). The large spacing was to accommodate the large (30–50 ha) home ranges of phascogales (Soderquist 1995). Elsewhere clusters of 2–4 boxes have been successful in supporting squirrel glider (*P. norfolcensis*) social groups over 10 years (Goldingay et al., 2015). Should chainsaw hollows be installed to support local populations of any species of arboreal mammal we would recommend installation in clusters. The spacing of clusters would need to be guided by home range size.

4.2. Change in cavity condition

For chainsaw hollows to be effective in habitat restoration, they need to be used by target species and maintain their integrity over time. Carey and Sanderson (1981) conducted trials in which cavities were drilled into 144 trunks of three different tree species in North America. After three years they found that 4% of trees had snapped at the cavity location, 4% had developed major cracks, 54% had callous around the cavity entrance, and 17% had callous occluding the entrance. Furthermore, 30% of cavities contained standing water and another 30% were damp. The three species showed differences in their susceptibility to fail and to callous over the entrance. In a subsequent study Carey (2002) constructed 128 chainsaw cavities with faceplates in trees. After two years, faceplates were replaced on 75% of cavities due to water ingress. The cavities were monitored for six years but no further information was provided on tree condition. Another approach has been used in restoration of red-cockaded woodpecker (*Picoides borealis*) habitat in North America in which a pre-made timber cavity is inserted into chainsaw hollows (e.g. Carrie et al., 1998; Saenz et al., 2001). This has proven successful in attracting birds to abandoned and previously unoccupied sites (Copeyon et al., 1991). The inserts have also been attractive to southern flying squirrels (*Glaucomys volans*) (Franzreb, 1997). Rueegger (2017) constructed chainsaw cavities with faceplates in 16 trees of seven species in Australia. After two years no trees failed but substantial lateral callous growth had occurred across the faceplate. Two further studies have occurred in Australia involving chainsaw hollows cut into 43 trees. These studies had a focus on cavity temperatures (Griffiths et al., 2018) and visitation to different cavity types (chainsaw versus natural) (Griffiths et al., 2020) and consequently did not report on changes in tree or cavity condition. We observed no tree failures but observed callous growth across the faceplates of some species that will require maintenance at some point. We also found substantial amounts of moisture in the cavities of trees of certain species. Our data suggest an inverse relationship between wound growth and moisture, which may mean those species with minimal wound growth may not seal the cavity and be more prone to cavity flooding. Despite the accumulation of moisture by some cavities we observed high rates of use by our target species across all chainsaw hollows. Further evaluation is required to understand whether moisture build up is a serious problem and if it affects rates of use. A cavity insert (e.g. Saenz et al., 2001) may be one way to manage this occurrence.

Throughout our study trees that contained chainsaw hollows remained intact. We used a conservative approach by not removing more than one third of each tree's diameter which limited the availability of suitable trees. Future projects may be able to take higher risks with the sizes of cavities in small diameter trees to investigate the limits of the sizes of cavities before trees fall. This information will be essential for restoration of young forests where larger hollows may be required in small diameter trees. This could also have important consequences for larger hollow dependent species that require larger hollows than the species we chose to investigate.

Nest boxes also showed some signs of deterioration towards the end of monitoring period. The lids of several boxes showed signs of peeling which may have been caused by chewing by parrots. This removal of the outer painted surface allowed water to penetrate the timber and cause mild warping of lids. Another study in this study landscape has documented a large percentage of nest boxes remaining functional for at least 20 years (Goldingay et al., 2018).

4.3. Conservation implications

There are many landscapes where the abundance of tree hollows has declined substantially from historical levels (Lindenmayer et al., 2014; Le Roux et al., 2016; Cockle et al., 2017). Hollow-using species have consequently declined in abundance and habitat restoration is now required to reverse (Gibbons et al., 2000; Saenz et al., 2001; Cockle et al., 2010; Goldingay, 2011). Our 2.5 year investigation has demonstrated the potential of chainsaw hollows to be more frequently occupied by hollow-using small mammals compared to traditional ply nest boxes. Our findings complement those of Griffiths et al., (2020) who demonstrated that chainsaw hollows attract a range of mammals and birds. In our case, we were able to demonstrate direct use and breeding by our target species.

Nest boxes have been employed in many cases to support hollow-using species where hollows are scarce. While our target species, brush-tailed phascogales and sugar gliders, showed a preference for chainsaw hollows, nest boxes were still used and have also been shown to be effective in other studies (Soderquist et al., 1996; Scida and Gration, 2017; Goldingay et al., 2018; Goldingay et al., 2020a,b). A successful conservation strategy for hollow dependent mammals may require the use of both types of artificial cavities.

We have identified several drawbacks to chainsaw hollows. Those of nest boxes are well documented. Further research with chainsaw hollows is required to investigate issues relating to occlusion of faceplates and water accumulation. We found different tree species responded differently to the carved hollows. Therefore, some tree species may not be suitable for long-term conservation programs. The hollows constructed in this study can be studied over several more years to provide further insight to their performance. Continued use (e.g. Saenz et al., 2001) by our target species will also test performance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank Ironbark Environmental-Arboriculture, Clifton Hill and Treetec, Menzies Creek for installing chainsaw hollows. We thank Karen Thomas (Bendigo Field Naturalists) for assisting with fieldwork. We thank owners of properties where chainsaw hollows were installed including Blair Venn, Mark Toohey, Ami Greenfield (Greater Shire of Bendigo), Michelle Wyatt (Macedon Ranges Shire Council), Jan Hall, Jane Rusden, Martin Tatton and Albert Golden. We thank Steve Griffiths for advice during the development of this study. All activities were conducted under an animal ethics permit from Southern Cross University (02/42).

References

Adkins, M.F., 2006. A burning issue: using fire to accelerate tree hollow formation in Eucalyptus species. Aust. For. 69 (2), 107–113.

Bennett, A., Lumsden, L., Nicholls, A., 1994. Tree hollows as a resource for wildlife in remnant woodlands: Spatial and temporal patterns across the northern plains of Victoria, Australia. Pacific. Biol. Conserv. 1, 222–235.

Bureau of Meteorology, 2011. Average annual, seasonal and monthly rainfall. http://www.bom.gov.au/jsp/ncc/climate_averages/rainfall/index.jsp (accessed 8 February 2021).

Beyer, G.L., Goldingay, R.L., 2006. The value of nest boxes in the research and management of Australian hollow-using arboreal marsupials. Wildlife Res. 33, 161–174.

Burnham, K.P., Anderson, D.R., 2004. Multimodel inference: understanding AIC and BIC in model selection. Sociol. Methods Res. 33, 261–304.

Carey, A., Sanderson, H., 1981. Routing to accelerate tree-cavity formation. Wildl. Soc. Bull. 9, 14–21.

Carey, A.B., Gill, J.D., 1983. Direct habitat improvements - some recent advances. In: Snag Habitat Management: Proceedings of the Symposium. USDA Forest Service General Technical Report RM-99 Fort Collins, Colorado, pp. 80-87.

Carey, A., 2002. Response of Northern Flying Squirrels to Supplementary Dens. Wildl. Soc. Bull. 30, 547–556.

Carrie, N.R., Moore, K.R., Stephens, S.A., Keith, E.L., 1998. Influence of cavity availability on red-cockaded woodpecker group size. Wilson Bull. 110, 93–99.

Cockle, K.L., Martin, K., Drever, M.C., 2010. Supply of tree-holes limits nest density of cavity-nesting birds in primary and logged subtropical Atlantic forest. Biol. Conserv. 143, 2851–2857.

Cockle, K.L., Martin, K., Wesołowski, T., 2011. Woodpeckers, decay, and the future of cavity-nesting vertebrate communities worldwide. Front. Ecol. Environ. 9, 377–382.

Cockle, K.L., Martin, K., Bodrati, A., 2017. Persistence and loss of tree cavities used by birds in the subtropical Atlantic forest. Forest Ecol. Manage. 384, 200–207.

Copeyon, C.K., Walters, J.R., Carter, J.H., 1991. Induction of red-cockaded woodpecker group formation by artificial cavity construction. J. Wildl. Manage. 55, 549–556.

Durant, R., Luck, G.W., Matthews, A., 2009. Nest-box use by arboreal mammals in a peri-urban landscape. Wildlife Res. 36, 565–573.

Edworthy, A.B., Martin, K., 2013. Persistence of tree cavities used by cavity-nesting vertebrates declines in harvested forests. J. Wildl. Manage 77 (4), 770–776.

Flesh, A.D., 2019. Patterns and drivers of long-term changes in breeding bird communities in a global biodiversity hotspot in Mexico. Divers. Distrib. 25, 499–513.

Franzreb, K.E., 1997. Success of intensive management of a critically imperiled population of red-cockaded woodpeckers in South Carolina. J. Field Ornithol. 68, 458–470.

Gibbons, D., Lindenmayer, D.B., Barry, S.C., Tanton, M.T., 2000. Hollow formation in eucalypts from temperate forests in south-eastern Australia. Pac. Conserv. Biol. 6, 218–228.

Gibbons, P., Lindenmayer, D.B., Barry, S.C., Tanton, M.T., 2002. Hollow selection by vertebrate fauna in forests of south-eastern Australia and implications for forest management. Biol. Conserv. 103, 1–12.

Goldingay, R.L., 2009. Characteristics of tree hollows used by Australian birds and bats. Aust Wildlife Res. 36, 394–409.

Goldingay, R.L., 2011. Characteristics of tree hollows used by Australian arboreal and scansorial mammals. Aust. J. Zool. 59, 277–294.

Goldingay, R.L., 2015. Temperature variation in nest boxes in eastern Australia. Aust. Mammal. 37, 225–233.

Goldingay, R.L., 2017. Does nest box use reduce the fitness of a tree-cavity dependent mammal? Ecol. Res. 32, 495–502.

Goldingay, R.L., Stevens, J.L., 2009. Use of artificial tree hollows by Australian birds and bats. Wildlife Res. 36, 81–97.

Goldingay, R.L., Rueegger, N.N., Grimson, M.J., Taylor, B.D., 2015. Specific nest box designs can improve habitat restoration for cavity-dependent arboreal mammals. Restor. Ecol. 23, 482–490.

Goldingay, R.L., Thomas, K.J., Shanty, D., 2018. Outcomes of decades long installation of nest boxes for arboreal mammals in southern Australia. Ecol. Manage. Restor. 19, 204–211.

Goldingay, R.L., Quin, D.G., Talamo, O., Mentiplay-Smith, J., 2020a. Nest box revealed habitat preferences of arboreal mammals in box-ironbark forest. Ecol. Manage. Restor. 21, 131–142.

Goldingay, R.L., Rohweder, D., Taylor, B.D., 2020b. Nest box contentions: Are nest boxes used by the species they target? Ecol. Manage. Restor. 21, 115–122.

Griffiths, S.R., Semmens, K., Watson, S.J., Jones, C.S., 2020. Installing chainsaw-carved hollows in medium-sized live trees increases rates of visitation by hollow-dependent fauna. Restor. Ecol. 28, 1225–1236.

Griffiths, S.R., Lentini, P.E., Semmens, K., Watson, S.J., Lumsden, L.F., Robert, K.A., 2018. Chainsaw-carved cavities better mimic the thermal properties of natural tree hollows than nest boxes and log hollows. Forests. 9, 235.

Griffiths, S.R., Rowland, J.A., Briscoe, N.J., Lentini, P.E., Handasyde, K.A., Lumsden, L.F., Robert, K.A., 2017. Surface reflectance drives nest box temperature profiles and thermal suitability for target wildlife. PLoS ONE 12, e0176951.

Harley, D.K.P., 2006. A role for nest boxes in the conservation of leadbeater's possum (*Gymnobelideus leadbeateri*). Wildlife Res. 33, 385–395.

Holland, G., Alexander, J.S., Johnson, P., Arnold, A.H., Halley, M., Bennett, A.F., 2012. Conservation cornerstones: capitalising on the endeavours of long-term monitoring projects. Biol. Conserv. 145 (1), 95–101.

Kikuchi, K., Akasaka, T., Yamaura, Y., Nakamura, F., 2013. Abundance and use of cavity trees at the tree-and stand-levels in natural and plantation forests in Hokkaido, Japan. J. For. Res. 18 (5), 389–397.

Koch, A.J., Munks, S.A., Driscoll, D., Kirkpatrick, J.B., 2008. Does hollow occurrence vary with forest type? A case study in wet and dry *Eucalyptus obliqua* forest. Forest Ecol. Manage. 255 (12), 3938–3951.

Le Roux, D.S., Ikin, K., Lindenmayer, D.B., Bistricer, G., Manning, A.D., Gibbons, P., 2016. Enriching small trees with artificial nest boxes cannot mimic the value of large trees for hollow-nesting birds. Restor. Ecol. 24, 252–258.

Lindenmayer, D.B., Laurence, W.F., Franklin, J.F., Likens, G.E., Banks, S.C., Blanchard, W., Gibbons, P., Ikin, K., Blair, D., McBurney, L., Manning, A.D., Stein, J. A., 2014. New Policies for Old Trees: Averting a Global Crisis in a Keystone Ecological Structure. Conserv. Lett. 7, 61–69.

Lindenmayer, D.B., Welsh, A., Donnelly, C., Crane, M., Michael, D., Macgregor, C., McBurney, L., Montague, R., Gibbons, P, 2009. Are nest boxes a viable alternative source of cavities for hollow-dependent animals? Long-term monitoring of nest box occupancy, pest use and attrition. Biol. Conserv. 142 (1), 33–42.

Lunt, I., 1988. Observations on the behaviour of the brush-tailed phascogale (*Phascogale tapoatafa*) at Black Hill, Victoria. Victorian Nat. 105, 41–42.

Mansfield, C., Arnold, A.H., Bell, T.L., York, A., 2017. Habitat characteristics of a threatened arboreal marsupial and its resource use in a degraded landscape: the brush-tailed phascogale (*Phascogale tapoatafa* tapoatafa) in central Victoria, Australia. Wildlife Res. 44, 153–164.

Mattheck, C., Bethge, K., West, P.W., 1994. Breakage of hollow tree stems. Trees 9, 47–50.

McDowell, N.G., Allen, C.D., Anderson-Teixeira, K., Aukema, B.H., Bond-Lamberty, B., Chini, L, et al., 2020. Pervasive shifts in forest dynamics in a changing world. Science 368 (6494).

Mine, K., Yamada, A., Nanri, T., Maruyama, K., Nakamura, H., Saigusa, M., 2014. Effect of nestbox provisioning on breeding density of dollarbirds (*Eurystomus orientalis*). Pac. Sci. 68, 365–374.

Morris, P.A., Bright, P.W., Woods, D., 1990. Use of nestboxes by the dormouse *muscardinus avellanarius*. Biol. Conserv. 51, 1–13.

Nichols, J.D., Bailey, L.L., O'Connell Jr., A.F., Talancy, N.W., Campbell Grant, E.H., Gilbert, A.T., Annand, E.M., Husband, T.P., Hines, J.E., 2008. Multi-scale occupancy estimation and modeling using multiple detection methods. J. Appl. Ecol. 45, 1321–1329.

Quin, D.G., Smith, A.P., Green, S.W., Hines, H.B., 1992. Estimating the home ranges of sugar gliders (*Petaurus breviceps*) (Marsupialia: Petauridae), from grid-trapping and radiotelemetry. Wildlife Res. 19, 471–487.

Rhind, S.G., 2003. Communal nesting in the usually solitary marsupial, *Phascogale tapoatafa*. J. Zool. 261, 345–351.

Rhind, S.G., Bradley, J.S., 2002. The effect of drought on body size, growth and abundance of wild brush-tailed phascogales (*Phascogale tapoatafa*) in south-western Australia. Wildlife Res 29 (3), 235–245.

Rowland,, J.A., Briscoe, N.J., Handasyde, K.A., 2017. Comparing the thermal suitability of nest-boxes and tree-hollows for the conservation-management of arboreal marsupials. Biol. Conserv. 209, 341–348.

Rueegger, N., 2017. Artificial tree hollow creation for cavity-using wildlife – trialling an alternative method to that of nest boxes. Forest Ecol. Manage. 405, 404–412.

Saenz, D., Conner, R.N., Collins, C.S., Rudolph, D.C., 2001. Initial and long-term use of inserts by red-cockaded woodpeckers. Wildl. Soc. Bull. 29, 165–170.

Saunders, D.A., Dawson, R., Mawson, P.R., Cunningham, R.B., 2020. Artificial hollows provide an effective short-term solution to the loss of natural nesting hollows for Carnaby's Cockatoo *Calyptorhynchus latirostris*. Biol. Conserv. 245, 108556.

Scarff, F.R., Rhind, S.G., Bradley, J.S., 1998. Diet and foraging behaviour of brush-tailed phascogales (*Phascogale tapoatafa*) in the jarrah forest of south-western Australia. Wildlife Res. 25, 511–526.
Scida, M., Gration, R., 2017. Monitoring the threatened brush-tailed phascogale (*Phascogale tapoatafa tapoatafa*) at sugarloaf reservoir, Victoria. Aust. Mammal. 40, 307–311.
Soderquist, T., 1993a. Maternal strategies of Phascogale tapoatafa (Marsupialia, Dasyuridae).1. Breeding seasonality and maternal investment. Australian J. Zool. 41, 549–566.
Soderquist, T., 1993b. Maternal strategies of Phascogale tapoatafa (Marsupialia, Dasyuridae).2. Juvenile thermoregulation and maternal attendance. Australian J. Zool. 41, 567–576.
Soderquist, T., 1995. Spatial organization of the arboreal carnivorous marsupial *Phascogale tapoatafa*. J. Zool. 237, 385–398.
Soderquist, T., Lill, A., 1995. Natal Dispersal and Philopatry in the Carnivorous Marsupial *Phascogale tapoatafa* (Dasyuridae). Ethology 99, 297–312.
Soderquist, T.R., Traill, B.J., Faris, F., Beasley, K., 1996. Using nest boxes to survey for the brush-tailed phascogale *Phascogale tapoatafa*. Vic. Nat. 113, 256–261.
Suckling, G.C., 1984. Population ecology of the sugar glider, *Petaurus breviceps*, in a system of fragmented habitats. Wildlife Res. 11, 49–75.
Traill, B.J., Coates, T.D., 1993. Field observations on the brush-tailed phascogale *Phascogale tapoatafa* (Marsupialia: Dasyuridae). Aust. Mammal. 16, 61–65.
van der Ree, R., Soderquist, T.R., Bennett, A.F., 2001. Home range use by the brush-tailed phascogale *Phascogale tapoatafa* (Marsupialia: Dasyuridae) in high-quality, spatially limited habitat. Wildlife Res. 28, 517–525.
van der Ree, R., Bennett, A.F., Soderquist, T.R., 2006. Nest-tree selection by the threatened brush-tailed phascogale (*Phascogale tapoatafa*) (Marsupialia: Dasyuridae) in a highly fragmented agricultural landscape. Wildlife Res. 33, 113–119.
Victorian State Government, 2020. Bioregions and EVC benchmarks. https://www.environment.vic.gov.au/biodiversity/bioregions-and-evc-benchmarks (accessed 11 February 2021).
Victorian State Government, 2003. Flora and Fauna Guarantee Act Action Statement No. 79. Department of Sustainability and Environment.
Wood, D., Wesley Burger Jr. L., Vilella, F., Raulston, B., 2000. Long-Term Effects of Red-Cockaded Woodpecker Cavity-Entrance Restrictors. Wildl. Soc. Bull. 28, 105-109.