Predicting how many trees contain hollows suitable for vertebrate fauna in forests of New South Wales

Philip Gibbons and Liam Connolly O'Donnell
Fenner School of Environment & Society
The Australian National University
March 2023

Summary

The aim of this report is to propose a methodology to predict how many hollow-bearing trees are perpetuated in forests of New South Wales managed under the Coastal Integrated Forestry Operations Approval (IFOA).

Because it typically takes over a century for suitable hollows to develop in trees of the genus *Eucalyptus*, ecological forecasting using simulation is a tractable way to predict how many hollow-bearing trees are perpetuated under the Coastal IFOA.

Simulation models typically predict how many trees occur in each diameter class through time and predict how many hollow-bearing trees occur in a stand based on relationships between the presence/absence of hollows recorded from the ground and tree diameter. However, published literature and data collected from felled trees in north-east NSW indicate that <50% of hollow-bearing are typically occupied by vertebrate hollow-dependent fauna. Thus, using tree diameter and tree species alone to predict how many hollow-bearing trees occur in NSW forests will over-estimate the number of hollow-bearing trees that are suitable for vertebrate fauna.

Our review of the literature and analysis of unpublished data indicated that trees are more likely to be suitable for occupancy by vertebrate hollow-dependent fauna where: (a) they contain multiple hollows visible from the ground (preferably ≥4); (b) they contain evidence of canopy senescence; and (c) they have a relatively large diameter for the tree species and site. Thus, future inventories and simulations of tree hollows should capture and model these data, which will improve predictions of which trees are likely to contain hollows suitable for hollow-dependent fauna.

Until improved data become available, we have proposed a method for simulating how many hollow-bearing trees occur within NSW forests managed under the Coastal IFOA using existing data and the Forest Resource and Management Evaluation System (FRAMES) developed and maintained by Forestry Corporation of NSW. This approach will provide estimates of the numbers of hollow-bearing trees that occur in forests managed under the Coastal IFOA and the proportions of these forests in which hollow-bearing trees are stable, increasing or declining through time.

Background

Approximately 100 vertebrate species, including many listed as Threatened, use tree hollows in the forests of New South Wales (Gibbons and Lindenmayer 1996). Hollow-bearing trees and future hollow-bearing trees suitable for these species are therefore intentionally retained in NSW native forests managed for wood production as part of conditions and protocols in the NSW Coastal Integrated Forestry Operations Approval (IFOA). The New South Wales Natural Resources Commission has sought advice on how to evaluate the effectiveness of the Coastal IFOA for providing hollow-bearing trees for hollow-dependent fauna.

The brief was as follows:

1. review available literature on the proportions of trees with hollows (observed from the ground) that contain hollows suitable for vertebrate fauna;
2. review available literature on the characteristics of trees that can be easily measured from the ground can be used to predict the likelihood that these trees contain hollows suitable for vertebrate fauna; and
3. provide recommendations to predict how many hollow-bearing trees are provided under the Coastal IFOA.

The proportion of trees with visible hollows that are occupied by fauna

Published studies in Australia indicate that 28% to 57% of trees with apparent hollows contain hollows suitable for occupancy by vertebrate fauna (Appendix 1). In the largest single study that collected data of this type from NSW, 45% of 842 hollow-bearing trees felled as part of the Pacific Highway upgrade in northern NSW contained hollows with evidence of occupancy by vertebrate fauna (Sandpiper Ecological 2016, Sandpiper Ecological 2017, Sandpiper Ecological 2020). In these studies a hollow was defined as having a minimum entrance width of 1cm (Sandpiper Ecological 2016, Sandpiper Ecological 2017, Sandpiper Ecological 2020) or 2cm (Gibbons, Lindenmayer et al. 2002, Koch, Munks et al. 2008). Thus, if hollow-bearing trees are predicted or selected based only on the presence/absence of hollows visible from the ground, approximately half of these trees will not be suitable for occupancy by vertebrate fauna. Results from 145 hollow-bearing trees observed before and after felling as part of the Pacific Highway upgrade in northern NSW indicated that 6% of hollow-bearing trees utilised by vertebrate fauna showed signs of hollow occupancy before the tree was felled. That is, it is difficult to reliably identify suitable hollow-bearing trees from the presence/absence of hollows visible from the ground or from direct signs of occupancy. Data in addition to the presence/absence of visible hollows are therefore required to improve the likelihood that hollow-bearing trees are suitable for hollow-dependent fauna.

Characteristics of hollow-bearing trees associated with occupancy by fauna

We reviewed 27 studies that examined the occupancy of trees by hollow-dependent fauna in *Eucalyptus*-dominated forests and woodlands (Appendix 1) and obtained data for 145 hollow-bearing trees measured before and after felling by Sandpiper Ecological Surveys as part of the Pacific Highway upgrade for Transport NSW. The frequency that different variables were significantly associated with the occupancy of hollows by at least one vertebrate species is illustrated in Figure 1. The relative importance (calculated as the sum of Akaike Weights) of variables associated with the occupancy of hollow-bearing trees by vertebrate fauna from felled trees inspected as part of the Pacific Highway upgrade (145 trees) are provided in Figure 2.

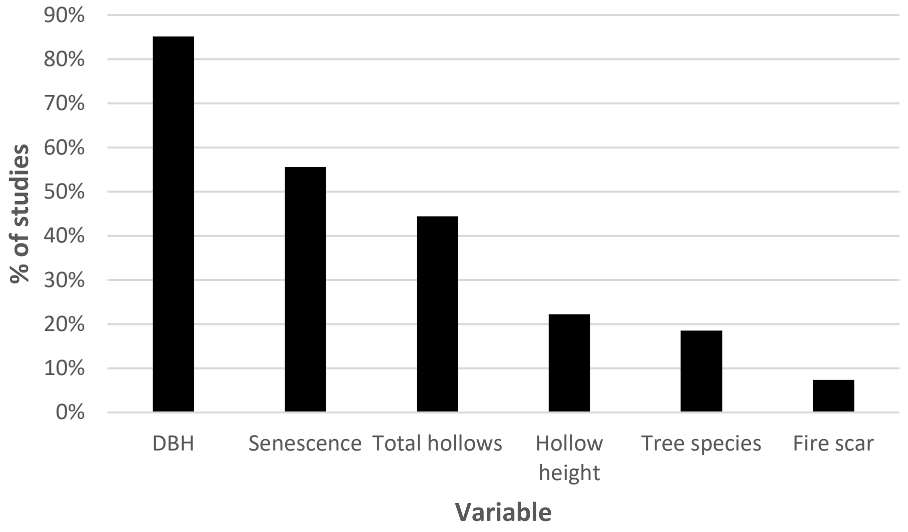

Figure 1. The % of studies (n=27) that identified DBH, crown senescence, total number of visible hollows, hollow height, tree species and/or the presence of a fire scar to be significantly associated with the occurrence of occupancy of hollow-bearing trees by hollow-dependent fauna. There was a positive association in all studies for all variables except hollow height (the owlet nightjar preferred hollows at lower heights) and tree species (a categorical variable). Note that not all variables were measured in each study.

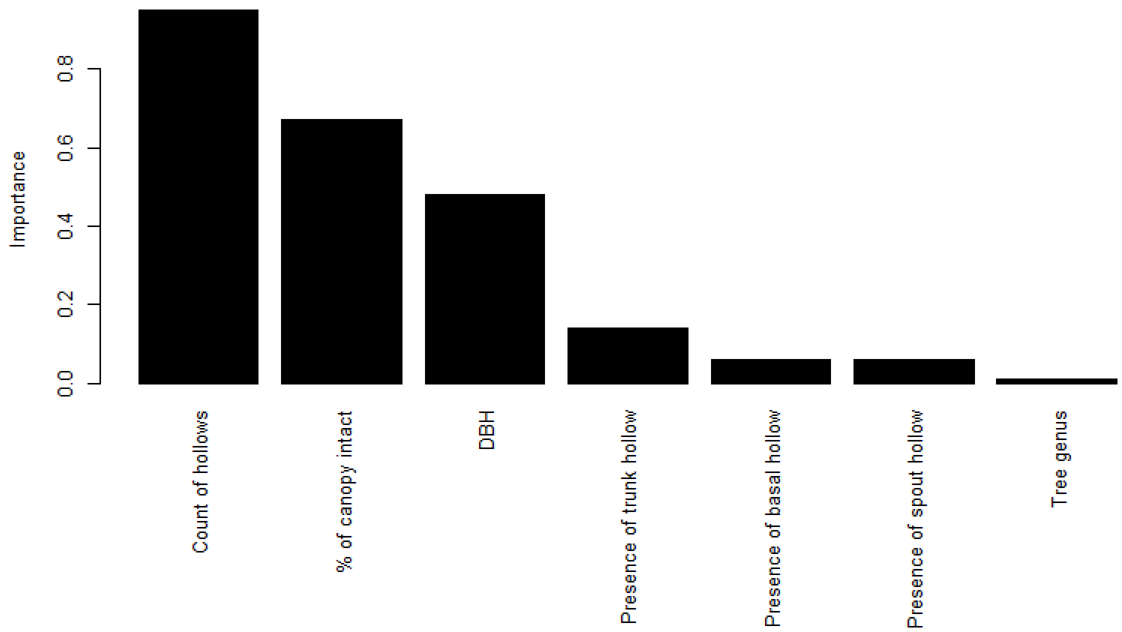

Figure 2. The relative importance (sum of Akaike Weights) of all variables used in generalised linear models used to predict which of felled hollow-bearing trees had evidence of occupancy by vertebrate hollow-dependent fauna based on data from 145 trees collected from works on the Pacific Highway in northern NSW by Sandpiper Ecological Surveys.

Tree diameter

The most common variable associated with trees suitable for hollow-dependent fauna was tree diameter, which appeared in 85% of studies (Figure 1). While hollow-dependent fauna have been observed in trees with relatively small diameters, the likelihood a tree contains hollows suitable for occupancy by fauna increases with DBH. For example, in East Gippsland, Victoria, hollow-bearing trees <50cm DBH were rarely occupied and only trees >140cm DBH had a likelihood of occupancy >50% (Gibbons, Lindenmayer et al. 2002). In southern NSW, the mean DBH of den trees used by the greater glider (*Petauroides volans*) was 114cm (Hofman, Gracanin et al. 2022). In marri (*Corymbia calophylla*) and jarrah (*E. marginata*) forest, trees became suitable as den sites for the brush-tailed phascogale (*Phascogale tapoatafa tapoatafa*) from 40cm DBH, but the mean DBH of den trees was 76 cm (jarrah) and 87cm (marri) (Rhind 1996). In the data obtained from the Pacific Highway upgrade in northern NSW, the smallest living eucalypt that contained at least one occupied hollow was 45cm DBH and most hollow-bearing trees with evidence of vertebrate fauna were >70cm DBH.

However, tree diameter is not typically the best variable that can be used to predict whether a hollow-bearing tree is suitable for vertebrate fauna. In studies that have examined occupancy of fauna in hollow-bearing trees, other variables (i.e., the number of hollows visible in the tree and degree of canopy senescence or growth stage) have more explanatory power (Brigham, Debus et al. 1998, Gibbons, Lindenmayer et al. 2002, Koch, Munks et al. 2008, Penton, Woolley et al. 2020). Tree diameter was not a significant variable in a model used to predict the number of vertebrate species occurring in hollow-bearing trees in East Gippsland, Victoria (Gibbons, Lindenmayer et al. 2002). This was also the case for data from the Pacific Highway upgrade. Data from this study indicated that the two variables with greatest ability to predict whether a hollow-bearing tree was occupied were the number of hollows visible in the tree and the % of the crown that was intact (Figure 3). That DBH is not the best predictor may be because these studies are all confined to sampling trees with hollows which typically occur in the larger DBH classes in a stand. Because the occurrence of hollows is strongly associated with DBH (Gibbons and Lindenmayer 2002), this variable becomes partly redundant when only hollow-bearing trees are considered. Further, different tree species attain different maximum diameters. For example, Gibbons et al. (2002) observed that the tree species in their study that attained the smallest maximum DBH was nevertheless one of the species with the highest rates of occupancy by fauna. Thus, where different tree species are included in a single study, this may confound the influence of DBH as a predictor.

Canopy senescence

Fifty-six per cent of reviewed studies included the degree of senescence, the proportion of the crown that contains dead branches or the number of dead branches as a predictor for occupancy of hollow-bearing trees (Figure 1 and Figure 3). That is, suitable hollows are most likely to occur in trees with visible signs of canopy dieback or senescence. For example, Smith et al. (2007) observed that the greater glider predominantly denned in trees that were late mature or over-mature. Gibbons et al. (2002) found that a tree was more likely to be occupied if >20% of the extant canopy was dead branches. And Koch et al. (2008) found that hollow-bearing trees were more likely to be occupied where they had a higher count of dead branches. That the degree of senescence in hollow-bearing trees is often a better predictor of occupancy than DBH is consistent with the suggestion that suitable hollows are associated with heartwood decay which, in turn, is more likely to occur in trees exhibiting canopy dieback (e.g., due to injury, disease or competition) or senescence (due to ageing) (Gibbons and Lindenmayer 2002) rather than in larger trees *per se*.

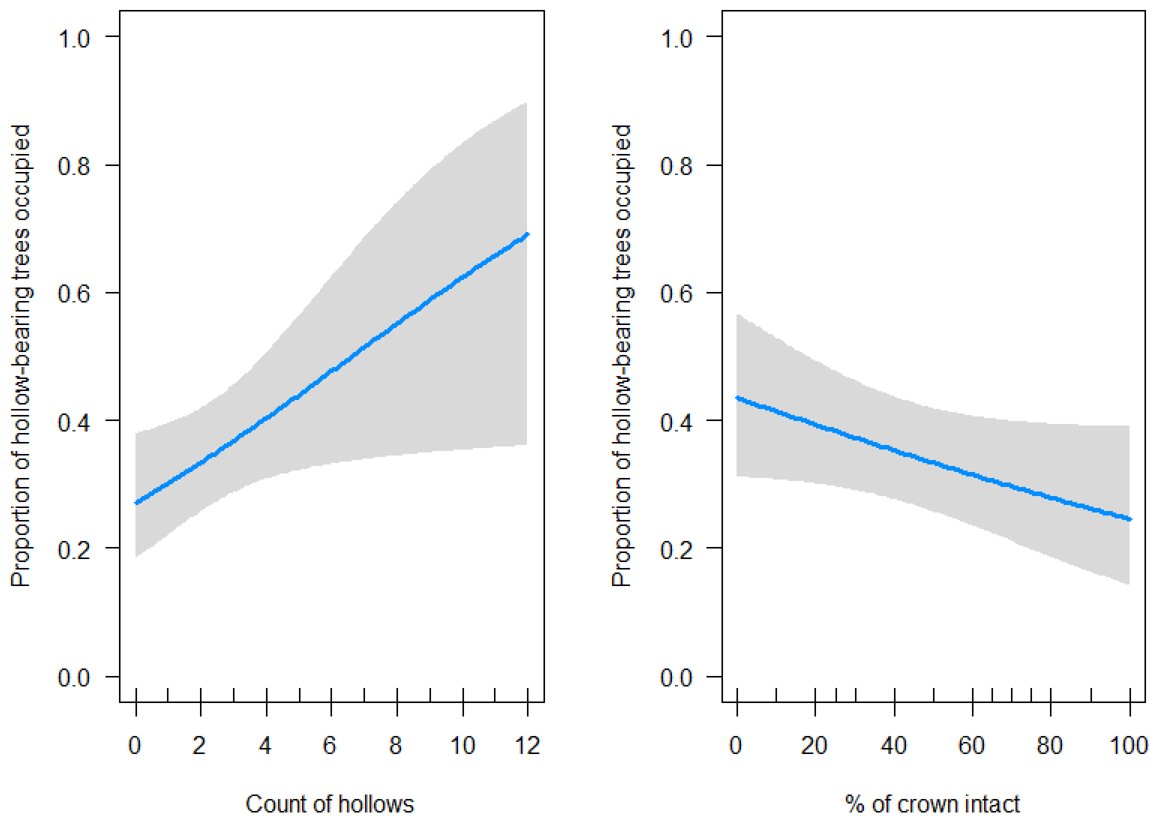

Figure 3. The variables that were able to most accurately predict the proportion (mean ± 95% confidence interval) of hollow-bearing trees that contain hollows suitable for occupancy by vertebrate fauna based on 145 living and dead trees of nine tree species felled as part of the Pacific Highway upgrade in northern NSW.

Count of hollows in the tree

Forty-four per cent of the reviewed studies (Appendix 1) reported that the likelihood a hollow-bearing tree contained suitable hollows increases with the number of visible hollows in the tree (figures 1-3). This was the best single variable for predicting whether a hollow-bearing tree was suitable for occupancy in most studies in which it was recorded (Brigham, Debus et al. 1998, Gibbons, Lindenmayer et al. 2002, Koch, Munks et al. 2008, Penton, Woolley et al. 2020). Gibbons and Lindenmayer (2002) speculated that the number of hollows in a tree is unlikely to be important for most fauna *per se*, but will increase the likelihood that at least one hollow is suitable for occupancy given most hollows identified from the ground are not suitable for occupancy by hollow-dependent fauna (Gibbons, Lindenmayer et al. 2002, Koch, Munks et al. 2008, Stojanovic, Rayner et al. 2021).

Other variables

Other variables associated with the suitability of hollow-bearing trees for vertebrate fauna were the height of the hollow, tree species, the occurrence of a fire scar or basal hollow, the entrance diameter and aspects of surrounding vegetation (figures 1-2 and Appendix 1). However, these variables appeared in 7-22% of the studies we reviewed so were not commonly associated with hollow-bearing trees suitable for occupancy by fauna, were not as good predictors of occupancy as the number of hollows visible in trees and canopy senescence in studies that also included these variables, and did not appear in the best models derived from the Pacific Highway data. That tree species is one of the less common variables that appears in these studies indicates the potential for generic guidelines for identifying suitable hollow-bearing trees based on the physical characteristics of trees.

Improving the identification of hollow-bearing trees from the ground

Results from data collected during the Pacific Highway upgrade in northern NSW indicate that hollow-bearing trees are likely to have >50% chance of being suitable for occupancy by vertebrate fauna only if they contain ≥4 visible hollows and <50% of the canopy is intact. From data collected for *E. fastigata, E. obliqua, E. cypellocarpa* and *E. croajingolensis* in East Gippsland, Victoria, Gibbons et al. (2002) found that trees had >50% chance of occupancy by hollow-dependent fauna only if they contained ≥2 hollows (visible on felled trees only) and this likelihood increased considerably only for trees with ≥4 hollows. In the same study, trees with multiple visible hollows were more likely to contain hollows suitable for occupancy by fauna if ≥20% of the extant canopy contained dead branches. Similarly, in Tasmania Koch et al. (2008) found that trees were significantly more likely to be occupied by fauna where they contained ≥2 hollows visible from the ground, the likelihood of occupancy increased with the count of dead branches and these authors predicted that trees were most likely to be occupied if they have ≥6 hollows visible from the ground. Our review of the literature and analysis of data from north-east NSW therefore suggest that trees are most likely to be suitable for occupancy by vertebrate hollow-dependent fauna where:

- They contain multiple hollows visible from the ground (preferably ≥4) AND
- Contain evidence of canopy senescence AND
- Have a large DBH for the tree species in the particular area.

These features of hollow-bearing trees are acknowledged in operational guidelines for selecting hollow-bearing trees in the field (NSW Environment Protection Authority 2020, Forestry Corporation of NSW 2021), but have not been employed within simulation models.

Recommended steps to evaluate how many hollow-bearing trees occur in forests managed under the Coastal IFOA

The Forest Resource and Management Evaluation System (FRAMES) developed and maintained by Forestry Corporation of NSW is principally used to model to availability of high-quality sawlogs over time (Forestry Corporation of NSW 2016). FRAMES contains the best models to predict how many hollow-bearing trees are perpetuated in forests of NSW managed under the Coastal IFOA and propose that this can be done using the following steps:

1. Configure FRAMES to predict the number of trees (by tree species group, per unit area, over time and by DBH class) across the range of feasible management scenarios that occur in forests managed under the Coastal IFOA. This will require predicting tree numbers by DBH class and species group under scenarios that represent: (a) stands with different histories of silvicultural treatment that are permanently protected as Environmentally Sensitive Areas (ESAs) within the Coastal IFOA; and (b) stands with different histories of silvicultural treatment that are within the net harvestable area. This modelling should focus initially on a single Timber Zone and for a time-frame of 200 years.

2. Develop models to predict the proportion of trees that contain hollows suitable for vertebrate fauna by DBH class and tree species group. The strategic forest inventory undertaken by Forestry Corporation of NSW contains ~4,500 plots that include data on DBH and the presence/absence of likely and visible hollows in each tree. Thus, the proportion of trees in each DBH class and species group that contain hollows can be predicted using data from this inventory (Figure 4). However, as

discussed previously, <50% of trees with visible hollows are suitable for occupancy by vertebrate fauna, so the number of hollow-bearing trees suitable for occupancy by fauna will be over-estimated if based on relationships between DBH and the presence of hollows visible from the ground measured in this inventory (Figure 4). More realistic estimates of hollow-bearing trees suitable for occupancy by vertebrate fauna can be obtained by multiplying the predicted proportion of trees in each DBH class and species group that contain hollows by the predicted proportion of hollow-bearing trees in the same DBH class and species group that are suitable for occupancy by fauna. These predictions are provided for 10 tree species on the lower north coast of NSW (Table 1) and three tree species in south-east NSW (Table 2), which were the only data sets available to the authors. This approach is limited by the availability of data on trees suitable for occupancy by hollow-dependent fauna and thus estimates must be made for other tree species and regions until more data become available.

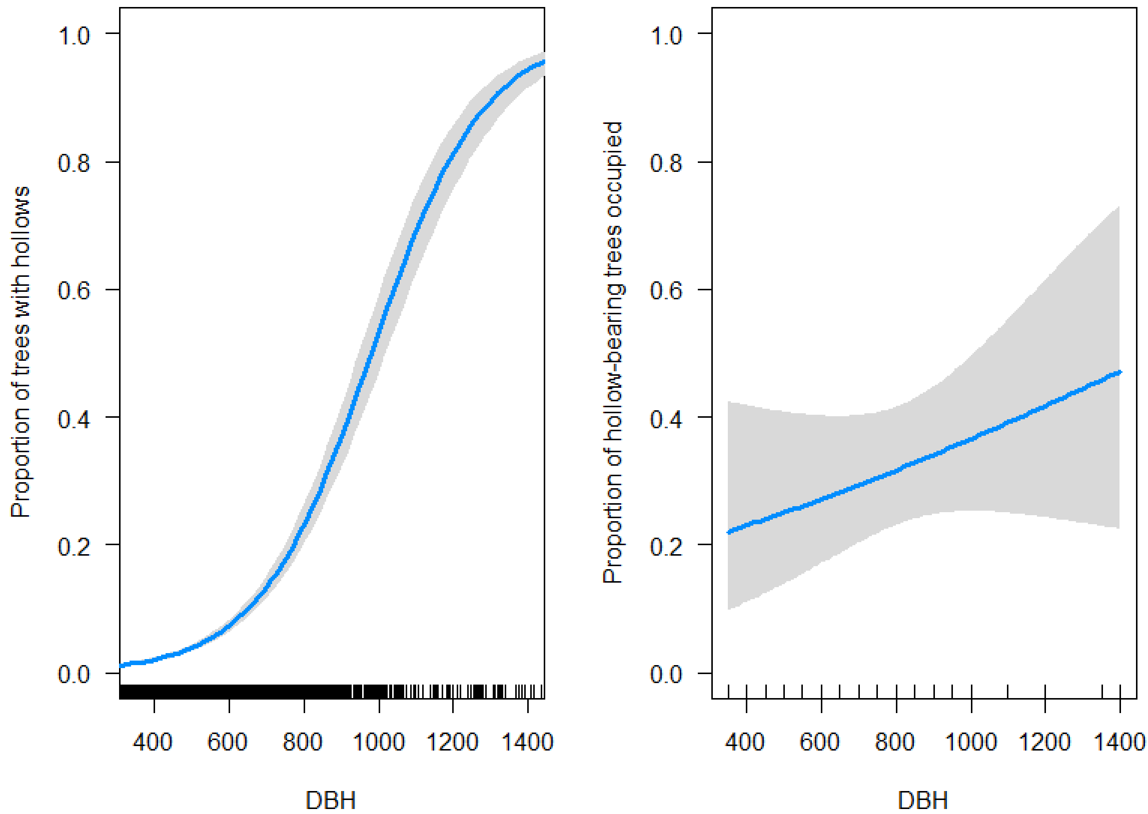

Figure 4. Predictions indicating the mean (± 95% confidence interval) proportion of living trees with hollows (n=11426 trees) derived from the Forestry Corporation of NSW's strategic forest inventory (left) and the mean (± 95% confidence interval) proportion of living hollow-bearing trees with evidence of occupancy by vertebrate fauna taken from felled trees (n=97 trees) (right). All predictions are for nine tree species from lower north-east NSW.

Table 1. Mean predicted proportions of living trees with hollows, the mean predicted proportions of living hollow-bearing trees suitable for occupation by fauna and the mean predicted proportions of all living trees suitable for occupation by fauna for nine tree species in north-east NSW.

DBH (mm)	Mean predicted proportion of trees with at least one hollow visible from the ground[1]	Mean predicted proportion of hollow-bearing trees occupied by fauna[2]	Mean predicted proportion of all trees suitable for occupation by fauna[3]
400	0.02	0.26	0.01
500	0.04	0.28	0.01
600	0.07	0.29	0.02
700	0.13	0.31	0.04
800	0.23	0.33	0.08
900	0.37	0.36	0.13
1000	0.53	0.38	0.20
1100	0.69	0.4	0.28
1200	0.81	0.42	0.34
1300	0.89	0.44	0.39
1400	0.94	0.47	0.44

[1] Predictions obtained from CRA forest inventory plots for n=11426 trees and nine tree species (*Eucalyptus acmenoides, E. globoidea, E. grandis, E. microcorys, E. pilularis, E. resinifera, E. robusta, E. tereticornis* and *Syncarpia glomulifera*) in lower north east NSW.

[2] Predictions obtained from n=97 felled trees and nine tree species (*Eucalyptus acmenoides, E. globoidea, E. grandis, E. microcorys, E. pilularis, E. resinifera, E. robusta, E. tereticornis* and *Syncarpia glomulifera*) from the Pacific Highway upgrade near Port Macquarie, NSW.

[3] Obtained by multiplying the mean predicted proportion of trees with at least one visible hollow × the mean predicted proportion of hollow-bearing trees occupied by fauna.

Table 2. Mean predicted proportion of living trees with hollows, the mean predicted proportion of living hollow-bearing trees suitable for occupation by fauna and the mean predicted proportion of all living trees suitable for occupation by fauna for three tree species in south-east NSW.

DBH (mm)	Mean predicted proportion of trees with at least one hollow visible from the ground[1]	Mean predicted proportion of hollow-bearing trees occupied by fauna[2]	Mean predicted proportion of all trees suitable for occupation by fauna
400	0.02	0.23	0.00
500	0.03	0.24	0.01
600	0.06	0.26	0.01
700	0.10	0.27	0.03
800	0.16	0.29	0.05
900	0.24	0.30	0.07
1000	0.36	0.32	0.11
1100	0.49	0.34	0.17
1200	0.63	0.35	0.22
1300	0.74	0.37	0.27
1400	0.83	0.39	0.33
1500	0.90	0.41	0.37
1600	0.94	0.43	0.40
1700	0.96	0.45	0.43
1800	0.98	0.47	0.46
1900	0.99	0.48	0.47
2000	0.99	0.50	0.50

[1] Based on data obtained for 2794 trees for *Eucalyptus fastigata, Eucalyptus obliqua* and *Eucalyptus cypellocarpa* in CRA inventory plots within south-eastern NSW.

[2] Based on data collected in 228 felled *E. fastigata, E. obliqua, E. cypellocarpa* and *E. croajingolensis* in East Gippsland, Victoria.

[3] Obtained by multiplying the mean predicted proportion of trees with at least one visible hollow × the mean predicted proportion of hollow-bearing trees occupied by fauna.

3. Undertake a sensitivity analysis for the predictions obtained from steps 1&2 above. This can be conducted using a Monte Carlo approach (i.e., where FRAMES is run several hundred times with the parameters in Table 3 changed randomly for each model run) or if this isn't feasible FRAMES can be run several times with the parameters in Table 3 varied systematically. The sensitivity of the predicted number of hollow-bearing trees over time to the input variables (Table 3) can then be analysed to identify those variables to which the predictions are most sensitive which will inform how the final simulation is undertaken at Step 4 and signals those variables for which better data are required in future.

Table 3. Variables that are likely to affect the number of hollow-bearing trees over the long-term and therefore should be tested in sensitivity analyses.

Variable
Initial DBH distribution of stand (forest stratum?)
The number of mature trees in the stand in addition to each hollow-bearing tree
The rate at which trees grow (in terms of DBH)
The rate at which trees form suitable hollows
Annual tree mortality/collapse
Tree mortality/collapse associated with fire
Fire interval
The proportion of trees are harvested in each DBH class

4. Use results from the sensitivity analysis in the previous step to make necessary adjustments to the way hollow-bearing trees are modelled using FRAMES.

5. Using the revised model from Step 4 above predict the number of hollow-bearing trees over time (200 years) under scenarios that represent: (a) stands with different histories of silvicultural treatment that are permanently protected as ESAs; (b) stands with different histories of silvicultural treatment that are within the net harvestable area; (c) separately for different Timber Zones; and (d) using different values for those parameters identified in the sensitivity analysis.

6. Use spatial data to calculate the proportions of each timber zone permanently protected in different ESAs under the Coastal IFOA and the proportion of each timber zone within the net harvestable area. Using these spatial data and predictions from FRAMES, estimate the proportions of each Timber Zone in which hollow-bearing trees: (a) are predicted to occur at different densities; and (b) are predicted to increase, remain stable or decline over time.

Acknowledgements

We would like to thank Scott Lawrence from Transport NSW and David Rohweder from Sandpiper Ecological for sharing unpublished data collected as part of the Pacific Highway upgrade and several members of the Forestry Corporation of NSW for sharing their knowledge about FRAMES.

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Appendix 1. Articles reviewed as part of this study.

Authors/Citation	Study Area	Species Assessed	DBH	Tree Senescence	Hollow Height	Total Number of Hollows	Other Predictors	Notes
Brereton, R 1997, *Management prescriptions for the swift parrot in production forests*, Joint Commonwealth and Tasmania RFA Steering Committee, Hobart, Tas.	Tasmania	Swift parrot (*Lathamus discolour*)	✓					- Ninety-six per cent of nests were in trees with a DBH greater than 70 cm. Entrance holes to nests were generally small, with a mean horizontal diameter of 10 cm and a mean vertical diameter of 10 cm. - Nest trees were significantly (65%) more likely to occur on a northerly to easterly aspect.
Brigham, RM, Debus, SJS, & Geiser, F 1998, 'Cavity selection for roosting, and roosting ecology of forest-dwelling Australian Owlet-nightjars (Aegotheles cristatus)', *Australian Journal of Ecology*, vol. 23, no. 5, pp. 424–429.	Eastwood State Forest, NSW	Australian Owlet-nightjar (*Agotheles cristatus*)			✓	✓	Proximity to other trees with hollows	- Owlet-nightjars spend more than half their time roosting, so cavities are critical resources. - Owlet-nightjars preferentially roosted in tree cavities ***closer*** to the ground, in trees with a significantly greater number of cavities and significantly closer to another tree with a cavity than expected by chance. - Telemetry data indicate that Owlet-nightjars move around 300 m between roost sites every 9 days on average. Individual birds used 2-6 different cavities during the 1-4-month period over which they were followed.
Cameron, M 2006, 'Nesting habitat of the glossy black-cockatoo in central New South Wales', *Biological Conservation*, vol. 127, no. 4, pp. 402–410.	Goonoo State Forest, NSW	Glossy black-cockatoo (*Calyptorhynchus lathami*)	✓	✓	✓	✓		- Glossy black-cockatoos nested in vertical spouts in large trees. - Nests were more likely to be located relatively high in senescent trees or standing dead trees (snags), factors most likely related to hollow suitability.
Cockburn, A & Lazenby-Cohen, KA 1992, 'Use of nest trees by *Antechinus stuartii*, a semelparous lekking marsupial', *Journal of Zoology*, vol. 226, no. 4, pp. 657–680.	Monga State Forest	Brown Antechinus (*Antechinus stuartii*)	✓	✓				- Young trees lack suitable cavities - No nest was used for longer than 22 months, though abandoned nests are often later re-used. - *A. stuartii* in this study are now reclassified as Agile Antechinus (*Antechinus agilis*)
Gibbons, P, Lindenmayer, DB, Barry, SC, & Tanton, MT 2002, 'Hollow selection by vertebrate fauna in forests of southeastern Australia and implications for forest management', *Biological Conservation*, vol. 103, no. 1, pp. 1–12.	East Gippsland, Victoria	Vertebrate fauna generally	✓	✓		✓	Tree form, fire scarring, tree species	- Of 228 hollow-bearing trees, 57% contained evidence of prior vertebrate occupancy. - Hollows that had been occupied rarely occurred in trees of less than 50 cm DBH. - Trees with more hollows, a large DBH and with a crown containing over 20% dead branches were likely to have a greater number of occupied hollows. - Externally visible variables of hollows, such as entrance width, could not be reliably used to predict whether a hollow was occupied. - Knowledge of individual fauna, particularly those of conservation concern, should also be employed when selecting trees for retention.
Goldingay, RL 2011, 'Characteristics of tree hollows used by Australian arboreal and scansorial mammals', *Australian Journal of Zoology*, vol. 59, no. 5, p. 277.	N/A (Literature review)	Various arboreal and scansorial mammals	✓	✓		✓		- Data are either deficient or absent for 85% of Australian hollow-using arboreal and scansorial mammal species. - Hollow abundance appears to be the primary determinant of tree preferences. This accounts for the frequent use of standing dead trees by most species. - Although tree size is of direct management relevance because it allows managers to rapidly ascertain the likelihood that hollows are available and the likely size of those hollows, it is the age of hollow-bearing trees that is particularly critical.

								- Most hollow-bearing trees used as dens are at least 100 years of age.
Goldingay, RL, Carthew, SM, & Daniel, M 2018, 'Characteristics of the den trees of the yellow-bellied glider in western Victoria', *Australian Journal of Zoology*, vol. 66, no. 3, pp. 179–184.	Rennick State Forest, Western Victoria	Yellow-bellied Glider (*Petaurus australis*)	✓	N/A	✓	N/A	Entrance diameter, tree height	- Entrance height (9 m) in dens was almost twice that of hollows in reference trees (5.5 m). The low absolute height reflects the forest in which the study was conducted, with trees averaging <20 m in height. In contrast, in tall mountain ash (*Eucalyptus regnans*) forest the average entrance height of yellow-bellied glider dens was 44 m. This suggests yellow-bellied gliders may prefer high den hollows in some forest types but the study shows they will tolerate a substantial variation in height. - While not significant, den trees tended to have narrower hollow entrances, deeper cavities and thinner walls than reference trees; cavities used by yellow-bellied gliders, on average, measured 36.8 cm deep and 18.0 cm in diameter, and had entrances 10.6 cm in diameter.
Harper, MJ, McCarthy, MA, van der Ree, R, & Fox, JC 2004, 'Overcoming bias in ground-based surveys of hollow-bearing trees using double-sampling', *Forest Ecology and Management*, vol. 190, no. 2–3, pp. 291–300.	Yarra Bend Park, Melbourne	N/A	N/A	N/A	N/A	N/A		**- Compared ground-based versus tree-climbing survey accuracy but not suitability of hollows for vertebrates.** - Ground surveyors who took more time with their surveys generally identified a higher proportion of hollows although all ground surveys underestimated hollow frequency, with ground-based surveyors identifying at most 44% of the total hollows. - Efficient surveys of hollow occurrence could be undertaken by inexperienced ground surveyors with periodic climbing surveys to measure and correct for bias.
Hofman, M, Gracanin, A, & Mikac, KM 2022, 'Greater glider (*Petauroides volans*) den tree and hollow characteristics', *Australian Mammalogy*, viewed 19 September 2022, <http://www.publish.csiro.au/?paper=AM22008>.	Seven Mile Beach National Park (SMBNP), NSW	Greater Glider (*Petauroides volans*)	✓	N/A	✓	N/A	Tree species	- Greater gliders appeared to be preferentially choosing dens based on tree species, DBH, hollow type/height/depth. Aspect, entrance diameter, and cavity wall thickness of hollows did not appear to be influencing den choice - Greater gliders in SMBNP preferred to den in blackbutt (*Eucalyptus pilularis*) with a mean DBH of 114.1 cm. Hollows were most commonly a 'branch end' type of hollow. Mean depth of hollows was 252 cm and mean hollow height was 15.4 m. - Greater gliders at SMBNP denned in hollows that were on average 15.4 m high (ranging from 8 to 25 m high). - No significant difference was found between ground and climbing surveys when estimating measurements of maximum entrance diameter, minimum and maximum cavity wall thickness, and depth (though depth had most deviation).
Koch, A, Munks, S, Driscoll, D, Koch, A, Munks, S, & Driscoll, D 2008, 'The use of hollow-bearing trees by vertebrate fauna in wet and dry Eucalyptus obliqua forest, Tasmania', *Wildlife Research*, vol. 35, no. 8, pp. 727–746.	Various sites across Tasmania's State Forest	Vertebrate fauna generally	✓	✓		✓		- Of the 319 hollow-bearing trees examined, 28% (88) showed evidence of use, which is at the lower end of the scale found in other areas of Australia. - Counting the number of hollows in standing trees was the best way to identify a tree that is likely to be used by fauna and this was particularly important for younger and healthier trees. - Estimated that 8–15 trees per hectare were used by hollow-using fauna in mature wet and dry *E. obliqua* forest in Tasmania.

Koch, AJ 2008, ‘Errors associated with two methods of assessing tree hollow occurrence and abundance in Eucalyptus obliqua forest, Tasmania’, *Forest Ecology and Management*, vol. 255, no. 3–4, pp. 674–685.	Various sites across Tasmania’s State Forest	N/A						**- Compared ground-based versus tree-felling survey accuracy but not suitability of hollows for vertebrates.** - For both ground and tree-felling surveys, the rate at which hollows were not detected was found to increase with tree size and hollow abundance. - Smaller hollows were more likely to be misidentified during ground-based surveys than larger hollows, particularly in trees that have little dead wood. - For both ground and tree-felling surveys, the rate at which hollows were not detected was found to increase with tree size and hollow abundance. - The destructiveness of tree-felling surveys brings its own inaccuracies, with 49.2% of hollows observed pre-fall surveys not detected post-felling due to smashing or obscuring.
Lindenmayer, DB, Cunningham, RB, Tanton, MT, Smith, AP, & Nix, HA 1991, ‘Characteristics of hollow-bearing trees occupied by arboreal marsupials in the montane ash forests of the Central Highlands of Victoria, south-east Australia’, *Forest Ecology and Management*, vol. 40, no. 3, pp. 289–308.	Central Highlands of Victoria	Arboreal marsupials	✓	✓		✓	Tree form	- Different species of arboreal marsupials exhibit preferences for hollow-bearing trees with different characteristics.
Lindenmayer, DB, Welsh, A, Donnelly, CF, & Cunningham, RB 1996, ‘Use of Nest Trees by the Mountain Brushtail Possum (Trichosurus Caninus) (Phalangeridae: Marsupialia). Ii. Characteristics of Occupied Trees.’, *Wildlife Research*, vol. 23, no. 5, pp. 531–545.	Cambarville, Central Highlands of Victoria	Mountain Brushtail Possum (*Trichosurus caninus)*				✓	Surrounding vegetation	- Trees likely to be used most frequently contained a relatively large number of cavities and were not surrounded by dense vegetation. - Findings indicate that *T. caninus* favours some types of hollow-bearing trees: although animals used up to 23 different trees, most spent the majority of their time denning in just 1-3 trees.
Luck, GW 2002, ‘The habitat requirements of the rufous treecreeper (Climacteris rufa). 1. Preferential habitat use demonstrated at multiple spatial scales’, *Biological Conservation*, vol. 105, no. 3, pp. 383–394.	Dryandra Woodland, Western Australia	Rufous Treecreeper (*Climacteris rufa*)					Hollow angle, entrance diameter	- Rufous treecreepers preferred hollows that had a spout angle greater than 50° to the horizontal and an entrance size of between 5 and 10 cm.
Penton, CE, Woolley, L-A, Radford, IJ, & Murphy, BP 2020, ‘Overlapping den tree selection by three declining arboreal mammal species in an Australian tropical savanna’, *Journal of Mammalogy*, vol. 101, no. 4, pp. 1165–1176.	Melville Island, Northern Australia	*Trichosurus vulpecula, Mesembriomys gouldii, Conilurus penicillatus*	✓		✓		Entrance diameter	- Unlike *T. vulpecula* and *M. gouldii,* the smaller *C. penicillatus* preferred smaller, dead trees, and its den sites were closer to the ground, including in hollow logs. - The two larger species had broader den tree use, using larger live trees and dens higher up in the canopy. - The apparent preference for larger tree cavities by all three arboreal species is concerning due to the limited availability of large trees across Australian savannas, which are subject to frequent, high-intensity fires.

Rayner, L, Ellis, M, & Taylor, JE 2011, 'Double sampling to assess the accuracy of ground-based surveys of tree hollows in eucalypt woodlands', *Austral Ecology*, vol. 36, no. 3, pp. 252–260.	Central-West NSW	N/A						**- Compared ground-based versus climbing survey accuracy but not suitability of hollows for vertebrates.** - Ground surveys are fairly reliable for identifying presence of hollows but much less so for estimating abundance and type of hollows. - 83% of hollow-bearing trees and 93% of trees without hollows were correctly classified by ground-based surveys. - A larger error was associated with the detection of hollows located in branches compared with hollows located in the main trunk. - Total number of hollows in the tree (based on climbing surveys), crown area or maximum trunk diameter were significant predictors of ground-based survey accuracy.
Rhind, SG 1996, 'Habitat tree requirements and the effects of removal during logging on the marsupial Brush-tailed Phascogale (Phascogale tapoatafa tapoatafa) in Western Australia', *The Western Australian Naturalist*, vol. 21, no. 1, pp. 1--22.	Near Manjimup, Western Australia	Brush-tailed Phascogale (*Phascogale tapoatafa tapoatafa*)	✓	✓				- Trees became markedly usable as habitat trees at above 40 cm DBH (over bark), with mean tree sizes of 87 cm DBH (Marri) and 76cm DBH (Jarrah). - Larger trees, especially those greater than 95cm DBH, represent higher quality habitat trees. - Logging resulted in an almost total removal of all potential habitat trees from logging coupes containing phascogales, and phascogales completely ceased nesting in those parts of their territories affected by logging. - *P. tapoatafa* continued to forage extensively throughout coupes which had been cut during logging, but confined nesting to trees within unlogged corridors between cut areas.
Rowston, C 1998, 'Nest- and refuge-tree usage by squirrel gliders, Petaurus norfolcensis, in south-east Queensland', *Wildlife Research*, vol. 25, no. 2, pp. 157–164.	South-east Queensland	Squirrel Glider (*Petaurus norfolcensis*)	✓	✓			Tree species	- Non-eucalypt trees and smooth-barked eucalypts were significantly under-utilised as nest trees. - Iron-barked eucalypts and stags were used as nest trees to a greater degree than would be expected from their availability in the environment. - Management of bushland to retain nesting sites for squirrel gliders should aim to retain dead and hollow-bearing rough-barked eucalypts, particularly ironbarks. A succession of age-classes of these trees is also required, to provide a continuous supply of nest trees
Shelton, MB, Phillips, SS, & Goldingay, RL 2020, 'Habitat requirements of an arboreal Australian snake (Hoplocephalus bitorquatus) are influenced by hollow abundance in living trees', *Forest Ecology and Management*, vol. 455, p. 117675.	Darling Downs, southern Queensland	Pale-headed Snake (*Hoplocephalus bitorquatus*)	✓	✓				- Snake detection was biased towards a riparian ecosystem where hollow-bearing tree density was on average nine times greater than adjoining vegetation communities. - Snakes selected live hollow-bearing trees that were significantly larger (mean DBH 74.5 cm) than those otherwise available and estimated to be on average 111 years old. - The lack of snakes encountered on dead hollow-bearing trees suggests they are not preferentially selected, irrespective of size, structure and abundance. This is likely linked to the different thermal properties of hollows in dead trees.
Smith, GC, Mathieson, M, Hogan, L, Smith, GC, Mathieson, M, & Hogan, L 2007, 'Home range and habitat use of a low-density population of greater gliders, Petauroides volans (Pseudocheiridae: Marsupialia), in a hollow-limiting environment', *Wildlife Research*, vol. 34, no. 6, pp. 472–483.	Barakula State Forest, southern Queensland	Greater glider (*Petauroides volans*)	✓	✓			Tree species	- Individual gliders surveyed utilised between 4 -20 den trees, with females using more than males. - Den tree species included the same species used for foraging as well as dead trees (16% of den trees). *E. fibrosa* and *E. tereticornis* were preferred significantly more than expected by their availability in the forest. - Large (dbh >50 cm) and old living trees (in deteriorating and senescent condition: 'late mature' and 'over-mature' categories) were primarily used as den trees. - It is likely that low availability of den trees is contributing to large home ranges and the apparent low population density observed in this study.

Stitt, JM, Svancara, LK, Vierling, LA, & Vierling, KT 2019, 'Smartphone LIDAR can measure tree cavity dimensions for wildlife studies', *Wildlife Society Bulletin*, vol. 43, no. 1, pp. 159–166.	Moscow, Idaho, USA	N/A						**- Experiment to test accuracy found that when varying height of target off the ground,** obliqueness of the viewing angle and distance from target, measurement error for both vertical and horizontal diameters of hollow entrances was <1 cm on average. - Used the Spike laser range-finding device which pairs with a mobile app to allow users to photograph tree hollow entrances (or other objects) on their phone or tablet and measure dimensions of the target onscreen.
Stojanovic, D, Rayner, L, Cobden, M, Davey, C, Harris, S, Heinsohn, R, Owens, G, & Manning, AD 2021, 'Suitable nesting sites for specialized cavity dependent wildlife are rare in woodlands', *Forest Ecology and Management*, vol. 483, p. 118718.	Northern ACT	Superb Parrot (*Polytelis swainsonii*)	✓			✓	Total hollow entrances (detected by climbing), stem diameter, entrance diameter	- Rarity of suitable cavities may be a factor limiting the population growth and recovery of superb parrots. - Hollows with the combination of traits suitable for Superb parrots comprised only 0.5% of the standing hollow resource. - Rather than relying on ground counts to estimate absolute numbers of tree cavities, the authors suggest they be used only as an index, and only in combination with other tree-level traits. - Conservation outcomes may be improved by protecting trees with 10 or more potential cavities as these trees are more likely to be a nesting site than not.
Stojanovic, D, Webb, M, Roshier, D, Saunders, D, & Heinsohn, R 2012, 'Ground-based survey methods both overestimate and underestimate the abundance of suitable tree-cavities for the endangered Swift Parrot', *Emu - Austral Ornithology*, vol. 112, no. 4, pp. 350–356.	South-eastern Tasmania	Swift Parrot (*Lathamus discolour*)	✓	✓	✓			- Most cavity-dependent species select tree-cavities with a narrow range of characteristics so that only a small subset of available cavities may be suitable for any species. - Scarcity of suitable cavities for Swift Parrots may result in poor conservation outcomes if forest management is based on a poorly performing index of cavity abundance derived from ground-based surveys. - Swift parrots prefer cavities with small entrances (mean minimum entry dimension of 5.7 cm), deep chambers and wide floors. - Ground-based surveys overestimated and underestimated the real number of cavities when DBH was 50 cm, but tended to overestimate the number when tree DBH increased. - Swift Parrot nest-trees had significantly larger DBH (mean = 102.43 cm) than randomly selected trees (mean = 84.81cm) - The number of cavities identified in ground-based surveys increased when more cavities were actually present in the canopy and with increasing tree DBH.
Taylor, RJ & Haseler, M 1993, 'Occurrence of potential nest trees and their use by birds in sclerophyll forest in north-east Tasmania', *Australian Forestry*, vol. 56, no. 2, pp. 165–171.	North-east Tasmania	*Pardalotus striatus*, *Dacelo novae-gaineae*, *Platycercus caledonicus*, *Calyptorhynchus funereus*	✓			✓	Fire scarring, tree species	- DBH and the presence of a fire scar explained one-third of the variation in numbers of hollows per tree. - *Eucalyptus viminalis* was used as a nest tree to a greater extent than expected from its relative abundance.
Taylor, RJ & Savva, NM 1988, 'Use of Roost Sites by Four Species of Bats in State Forest in South-Eastern Tasmania.', *Wildlife Research*, vol. 15, no. 6, pp. 637–645.	Near Woodsdale, south-eastern Tasmania	*Chalinobolus morio*, *Eptesicus regulus*, *Eptesicus sagittula*, Nyctophilus geofroyi	✓					- Large trees over 80 cm in diameter at breast height favoured. - No tendency to avoid roost sites close to the ground. - The factors associated with production of roost sites in trees were: large size, overmaturity, death, rot, and fire. - No bats were found to roost in regrowth forest. - Patches of mature forest need to be retained to ensure a shortage of roosts does not occur as more areas of mature forest are converted to production forest.

Tidemann, SC, Lawson, C, Elvish, R, Boyden, J, & Elvish, J 1999, 'Breeding Biology of the Gouldian Finch Erythrura gouldiae, an Endangered Finch of Northern Australia', *Emu - Austral Ornithology*, vol. 99, no. 3, pp. 191–199.	Yinberrie Hills and Newry Station, NT	Gouldian Finch (*Erythrura gouldiae*)	✓				Steep slopes, single-stemmed trees, entrance diameter	- Compared with other finches, nesting exclusively in hollows may confer some advantages on the breeding output of the Gouldian Finch. - The re-use of hollows 60% of the time by the same pair and independently by different pairs of Gouldian Finches suggests that either hollow availability is limiting or that some hollows, even with the same dimensions, are more suitable than others.
Watt, A 1991, *The ecology of three species of Antechinus (Marsupialia: Dasyuridae) in upland rainforests of north-east* Queensland. PhD Thesis, James Cook University, Townsville.	North-east Queensland	Brown Antechinus (*Antechinus stuartii*) and Yellow-Footed Antechinus (*Antechinus flavipes*)	✓			✓		
Webb, JK & Shine, R 1998, 'Using thermal ecology to predict retreat-site selection by an endangered snake species', *Biological Conservation*, vol. 86, no. 2, pp. 233–242.	Morton National Park, NSW	Broad-headed Snake (*Hoplocephalus bungaroides*)	✓	✓		✓		- During summer, broad-headed snakes spend long periods of time sequestered inside tree-hollows.
Webster, R 1988, *The superb parrot: a survey of the breeding distribution and habitat requirements*. Australian National Parks and Wildlife Service, Canberra.	South-east Australia	Superb Parrot (*Polytelis swainsonii*)	✓	✓			Number of dead/broken limbs, distance to watercourse	
Wood, MS & Wallis, RL 1998, 'Potential Competition for Nest Sites Between Feral European Honeybees (Apis mellifera) and Common Brushtail Possums (Trichosurus vulpecula).', *Australian Mammalogy*, vol. 20, no. 3, pp. 377–381.	You Yangs Regional Park, Victoria	Common Brushtail Possum (Trichosurus vulpecula)	✓			✓		- Feral European honeybees have the potential to displace arboreal marsupials; in 58% of trees with a bee colony, *T. vulpecula* were also detected.
Wormington, KR, Lamb, D, McCallum, HI, & Moloney, DJ 2003, 'The characteristics of six species of living hollow-bearing trees and their importance for arboreal marsupials in the dry sclerophyll forests of southeast Queensland, Australia', *Forest Ecology and Management*, vol. 182, no. 1, pp. 75–92.	South-east Queensland	Arborial marsupials	✓	✓				- Entrance diameters increased in trees with a larger DBH. - Concluded that a mixture of tree species provided a range of hollow sizes and positions that would be suitable for nesting and denning by arboreal marsupials in *Corymbia citriodora/Eucalyptus crebra* forests. - Hollow-bearing trees in general would be best retained in the State Forests of southeast Queensland in proportion to the overall tree species mix of any given area.