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Overcoming bias in ground-based surveys of hollow-bearing trees using double-sampling

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Abstract

Hollow-bearing trees are an important ecological resource for many forest-dwelling species throughout the world. Assessments of the abundance and characteristics of tree hollows usually involve ground-based surveys. These are likely to be biased because of the distance over which the assessments are made. We demonstrate the use of double-sampling theory to correct this bias in order to provide the most efficient estimate of hollow abundance. A sample of 40 *Eucalyptus leucoxylon* (yellow gum) trees located at Yarra Bend Park, Melbourne, were climbed and assessed for hollows through close-up inspection. The results were compared to ground-based surveys conducted by individuals with varying levels of experience in assessing tree hollows. Strong correlations ($r = 0.57 - 0.83$) were found between climbing and ground surveys and amongst ground surveys. Those ground surveyors who took more time with their surveys generally identified a higher proportion of hollows (Spearman's $r^2 = 0.72$), although all ground surveys underestimated hollow frequency. The proportion of hollows identified by each observer (range 0.09–0.44) remained approximately constant across all tree diameter size classes, indicating systematic underestimation of hollow frequency. The relative efficiency of ground surveys in comparison to climbing surveys is dependent on the time taken for each survey method and the strength of the relationship between them. Although climbing surveys provided the standard for hollow detection, in all cases, the quicker ground surveys were found to increase the efficiency of hollow assessments. Therefore, it was determined that efficient surveys of hollow occurrence could be undertaken by inexperienced surveyors with periodic climbing surveys to measure and correct for bias.

Keywords: Tree hollows; Ground surveys; Climbing surveys; Efficiency; Correction factor; *Eucalyptus leucoxylon*

1. Introduction

Hollow-bearing trees are an important ecological resource for many forest-dwelling species throughout the world (Ranius and Wilander, 2000; Gibbons and Lindenmayer, 2002; Eltz et al., 2003; Lohmus, 2003). For example, over 303 Australian vertebrate species use hollows for either permanent or temporary refuge and breeding sites, approximately 100 of which are considered rare or threatened (Gibbons and Lindenmayer, 2002). Managing the abundance of tree hollows in forest areas is critical to the persistence of hollow-dependent fauna; prescriptions to achieve this

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in timber production areas are routinely employed (Department of Conservation and Environment, 1992). Implementation of such management strategies, and monitoring their success relies on the accurate identification of hollow-bearing trees. Ecological research on hollow-dwelling fauna also often relies on accurate assessments of hollow occurrence (Lindenmayer et al., 1991).

Due to time, safety, and financial constraints, most surveys of hollow-bearing trees have utilised ground-based survey techniques (Lindenmayer et al., 1993, 2000; Bennett et al., 1994; Wormington and Lamb, 1999). These usually involve scanning the tree with binoculars from the ground, and recording the number and characteristics of the hollows that are observed. Potential problems exist with such a technique, including: (1) hollows on top of branches are not visible from below; (2) hollows may be obscured by limbs and/or foliage; (3) hollows occurring higher in the canopy may be difficult to detect; (4) vantage points from which to assess the trees may be unavailable due to nearby trees or obstacles; and (5) it is not possible to accurately determine the depth and other internal characteristics of hollows from the ground.

Hollow depth is significantly associated with evidence of prior occupancy (Gellman and Zielinski, 1996; Gibbons and Lindenmayer, 2002). Due to the difficulties in estimating hollow depth, ground surveyors may base decisions of what constitutes a hollow chiefly on the presence of an identifiable hollow entrance. Such decisions are likely to be inaccurate because the depth of a hollow is only weakly positively related to its minimum entrance width (Gibbons et al., 2000). It follows that correction for bias in assessing suitable hollows will be necessary.

The accuracy of ground-based surveys of tree hollows has been analysed through comparison of initial ground surveys of standing trees with surveys after the tree has been felled (e.g. Mackowski, 1984; Gibbons, 1999; Whitford, 2001; Whitford and Williams, 2002). Such analyses indicated that counting hollows from the ground might be inaccurate. However, such destructive sampling of trees may be impractical or counter-productive in ecologically sensitive areas. The reliability of this technique is also reduced if hollows are destroyed or created through mechanical damage as the tree is felled or if hollows that survive the fall are obscured once on the ground.

In this paper, we use double-sampling theory to efficiently overcome bias in ground-based surveys. Bias refers to the underestimation of hollow frequency displayed by each ground observer in relation to the number of hollows counted during the climbing assessment. We recorded the level of bias in ground-based surveys of hollows, variations in the bias displayed amongst surveyors, and the relative efficiency of ground-based surveys in relation to more accurate methods. To overcome the potential inaccuracy associated with comparing hollow observations of standing and felled stems, a non-destructive method of hollow assessment was used; a qualified arborist climbed standing trees and all hollows were assessed.

2. Methods

2.1. Study area and tree selection

This study was undertaken in a 1.5 ha area of dry sclerophyll forest within Yarra Bend Park near Melbourne, southeastern Australia. Dominated by yellow gum (*Eucalyptus leucoxylon*), the study site forms part of a larger tract (ca. 260 ha) of open eucalypt woodland, some of the most extensive in metropolitan Melbourne. Trunk diameter at breast height (DBH 1.3 m) and tree height were measured for each tree on the study plot, a minimum DBH of 20 cm was set for the analysis. Height was measured with a hand-held clinometer and tape measure, and DBH was measured with a diameter tape. All *E. leucoxylon* trees were placed into one of the four following DBH categories: 20–34, 35–49, 50–64 and >65 cm. Assessments were undertaken on a sample of 40 trees, 10 being randomly selected from each size class.

2.2. Hollow assessment method

Hollows with an entrance diameter of less than 1 cm were excluded from the analysis due to time constraints, the large volume of potential hollows in this size class, and the difficulty in identifying such hollows from the ground (i.e., habitat for microchiropteran bats was excluded). For both ground and climbing surveys, in order to be classified as a hollow, a cavity with an entrance diameter of less than 5 cm was required to be at least 5 cm deep. Where the entrance diameter was >5 cm, the hollow was only recorded if its depth was greater than its diameter. Hollows were categorised according to form and location within the tree (refer to Lindenmayer et al., 2000). Specifically, these were trunk top, trunk main, branch end (including bayonet type) and butt. Longitudinal splits or cracks in the structure of the tree (fissures) were not recorded per se, however, hollows formed in or about fissures were placed into categories dependent on the characteristics previously outlined. For example, if a hollow of the required minimum dimensions occurred inside a fissure on the tree trunk, it was record as a trunk hollow. The methods employed for both climbing and ground-based surveys are set out below.

Climbing-based direct inspections. Qualified arborists (MH and one assistant) surveyed trees from within the canopy. Surveys from within the canopy involved setting ropes at the highest possible point within the tree and systematically assessing each branch for hollows whilst descending. All recordings of hollows were made by the arborist whilst in the tree and kept confidential until all ground surveys had been undertaken. To limit climber bias, the survey was undertaken by just two arborists with random inter-checking of observations. The time taken to climb and assess each tree was recorded.

Ground-based surveys. Nine individuals were ranked depending on their level of experience at assessing tree hollows from the ground. In this analysis experience refers to the total number of hours each surveyor has previously spent undertaking ground-based surveys of tree hollows. Each surveyor scanned each of the same 40 trees using binoculars; recording specified hollow characteristics and the time taken for each survey. Reference photos were used to instruct each ground and climbing surveyor as to the correct classification of hollows before surveys commenced. All surveys were undertaken in August 2002 at the same time of day during fine weather.

2.3. Data analysis

The number of hollows observed through climbing was initially compared to the results of the ground-based surveys using correlation analysis and calculating the relative proportion of hollows observed. These relationships were further examined using generalised linear models (GLM) (McCullagh and Nelder, 1983). Logistic and Poisson regression were used to produce GLMs of both the probability of finding a hollow and the expected number of hollows per tree, respectively. The DBH of the tree was used as the only explanatory variable in all models. Type III Wald tests were used to determine statistical significance of the models. Models produced using data from the nine ground-based surveys were compared to those produced using the data from the climbing surveys. Generalised linear mixed models (GLMM) (McCullagh and Nelder, 1983) were produced to assess whether there were statistically significant differences between ground-based observers, with observers treated as a random effect. Statistical analyses were undertaken using SAS Institute (1996), and GLMMs were estimated using the GLIMMIX macro (Wolfinger and O'Connell, 1993).

To determine the most efficient method of surveying tree hollows, both the time taken for the survey and the accuracy of the survey must be considered. An inaccurate method may be more efficient if the time-saving allows a sufficiently larger sample size to be taken and if any bias can be corrected. This trade-off between two methods (speed versus accuracy) can be assessed using double-sampling theory (Gilbert, 1987). Double-sampling involves a comparison of the ratio of the time taken for the two methods of survey to a critical ratio that takes into account the strength of the relationship between the survey methods. If there is a strong correlation between the results of the survey methods, and the inaccurate method is sufficiently fast compared to the accurate method, then it may be more efficient to use the inaccurate but quicker method of survey. The less accurate method will be favoured provided it is sufficiently accurate for the time saving involved. This can be determined by calculating a critical ratio (Gilbert, 1987)

$$\text{Critical ratio} = \frac{\left(1+\sqrt{1-\rho^2}\right)^2}{\rho^2}, \quad (1)$$

where ρ is the correlation between the results of the ground and climbing surveys. If the time taken by the accurate method divided by the time taken by the inaccurate method is greater than this critical ratio, double-sampling (i.e., using the inaccurate method) is efficient (Gilbert, 1987).

Visual bias is a problem encountered in many ecological surveys (Caughley, 1974; Packard et al., 1985; Bulinski and McArthur, 2000). If the obstacles to visual survey cannot be incorporated into the sampling design then the bias of the sampling methodology should be measured. Estimates of bias can then be used to increase the compatibility between the observed and actual estimates (Caughley, 1974; Packard et al., 1985). Bias associated with the individual observer (e.g., level of experience, choice of observation position, visual impairment) makes it necessary to apply individual "correction factors". Correction factors may be formulated through a range of regression techniques (Caughley, 1974). In this study, simple linear regression was used to make the results of ground-based surveys compatible with the climbing surveys, with all error assumed to be in the former.

3. Results

3.1. Hollow occurrence in climbing surveys

The mean number of hollows found per tree (based on climbing-based surveys) was 7.8 ($n = 40$, range 0–35). Hollows occurred most often in the tree canopy and least often in the main trunk (branch middles 45%, branch ends 47%, trunk 6%, trunk top 2% and trunk butt 1%, $n = 311$).

A positive relationship was observed between number of hollows and the DBH of the tree ($r^2 = 0.77$). Eighteen out of 20 trees >50 cm DBH contained at least one hollow with the exceptions being specimens of 53 and 58 cm DBH. The relationship between height of a tree and the number of hollows was weak ($r^2 = 0.30$), this is most likely to be due to a lack of variation in tree height across the sample. Trees of narrow diameter (DBH <50 cm), which were rarely observed to be hollow-bearing, were most often 10–15 m in height, whilst the largest trees in the survey (>75 cm DBH) did not exceed 19.5 m in height. Regression models were constructed for both the probability of a tree being hollow-bearing (containing at least one hollow) and the estimated absolute number of hollows >1 cm diameter. Both models used DBH as a lone explanatory variable. The model:

$$\ln\left(\frac{p}{1-p}\right) = -5.08 + 0.121\,\mathrm{DBH}, \tag{2}$$

where p is the probability of hollow occurrence, explains 41% of the observed deviance in hollow occurrence ($P < 0.05$).

Similarly the model:

$$\ln(H) = -0.3245 + 0.0400\,\mathrm{DBH}, \tag{3}$$

where H refers to the number of hollows, explained 53% of the observed deviance in the absolute number of hollows per tree ($P < 0.05$).

3.2. Accuracy of ground observations in comparison to climbing surveys

3.2.1. Hollow-bearing/non-hollow-bearing

The proportion of trees correctly identified as containing hollows was high (mean = 0.82) and ground observers were similarly able to correctly identify a high proportion of non-hollow-bearing trees (mean = 0.89) (Table 1). A GLMM constructed from pooled data (observers 1–9) indicated that one ground surveyor (#6) underestimated the probability of hollow occurrence and achieved results significantly different from other ground surveys ($t = -3.12$, $P = 0.001$) (Table 2).

3.2.2. Hollow frequency

Correlations between the number of hollows detected through climbing and ground-based surveys were positive. For eight of the nine ground-based

Table 1
All ground observers correctly identified a high proportion of trees as being either hollow-bearing or non-hollow-bearing (1: most experienced ground surveyor; 9: least experienced ground surveyor)

Surveyor	Proportion of trees correctly identified as hollow-bearing	Proportion of trees correctly identified as non-hollow-bearing
1	0.83	0.88
2	1.00	0.89
3	0.91	0.88
4	0.79	1.00
5	0.92	0.88
6	0.50	0.94
7	0.84	0.80
8	0.75	0.94
9	0.83	0.81
Mean	0.82	0.89

Table 2
Solutions for the random effect (surveyor) in the GLMM estimating the probability of hollow occurrence. Surveys significantly different from the pooled data ($P < 0.05$) are shown in bold

Surveyor	Estimate	Pred	d.f.	t-Value	P
1	0.1207	0.4007	350	0.30	0.7634
2	0.1207	0.4007	350	0.30	0.7634
3	0.4308	0.4020	350	1.07	0.2847
4	−0.3421	0.4008	350	−0.85	0.3940
5	0.4308	0.4020	350	1.07	0.2847
6	**−1.2808**	**0.4101**	**350**	**−3.12**	**0.0019**
7	0.5867	0.4031	350	1.46	0.1465
8	0.2755	0.4012	350	0.69	0.4928
9	−0.3421	0.4008	350	−0.85	0.3940

Table 4
Solutions for the random effect (surveyor) in the GLMM estimating the number of hollows[a]

Surveyor	Estimate	Pred	d.f.	t-Value	P
1	0.1424	0.2149	350	0.66	0.5078
2	**0.4666**	**0.2057**	**350**	**2.27**	**0.0239**
3	**0.5028**	**0.2048**	**350**	**2.45**	**0.0146**
4	−0.01835	0.2203	350	−0.08	0.9337
5	0.1324	0.2152	350	0.62	0.5387
6	**−0.7832**	**0.2553**	**350**	**−3.07**	**0.0023**
7	**0.5099**	**0.2046**	**350**	**2.49**	**0.0132**
8	−0.3375	0.2330	350	−1.45	0.1483
9	**−0.6150**	**0.2463**	**350**	**−2.50**	**0.0130**

[a] Surveys significantly different from the pooled data ($P < 0.05$) are shown in bold.

surveys, the correlation ranged from 0.70 to 0.83, with a single lower value of 0.57 (Table 3). The proportion of hollows recorded from the ground, relative to climbing, varied amongst ground surveyors (mean = 0.28, range 0.09–0.44) (Table 3). A moderate positive correlation was found between the level of experience of the ground surveyor and the proportion of hollows they found during their survey (Spearman's $r^2 = 0.52$). However, regardless of experience, those ground surveyors who took more time over their surveys generally found more hollows (Spearman's $r^2 = 0.72$) and achieved lower correction factors (Table 3). Five of the nine ground surveys differed significantly from a GLMM formulated from pooled data (Table 4).

With the exception of a single ground surveyor (#2), the proportion of hollows identified by ground-based surveyors remained relatively constant across all four size classes of trees indicating a systematic underestimation of hollows (Fig. 1).

3.3. Efficiency of ground surveys

Double-sampling (ground-based surveys with periodic climbing surveys to correct for bias) was determined to be the most efficient survey option for all observers. In all cases, the actual ratio of time taken for the climbing survey compared to the ground survey exceeded the critical ratio (Fig. 2).

Table 3
Correlation between individual ground surveys and the climbing survey, the proportion of hollows identified by each ground surveyor in relation to the climbing survey, the time taken for all surveys and the correction factor for ground surveyors[a]

Surveyor	Correlation with climbing survey	Proportion of hollows identified	Time taken for assessments	Correction factor
Climbing survey	n/a	n/a	1271	n/a
1	0.82	0.30	209	3.72
2	0.85	0.42	161	2.59
3	0.81	0.44	225	2.43
4	0.83	0.25	98	4.30
5	0.81	0.28	93	3.80
6	0.57	0.09	99	11.11
7	0.80	0.44	161	2.43
8	0.70	0.17	71	7.05
9	0.75	0.13	87	8.45

[a] Surveyors are ranked 1–9 according to the level of experience (1 being the most experienced).

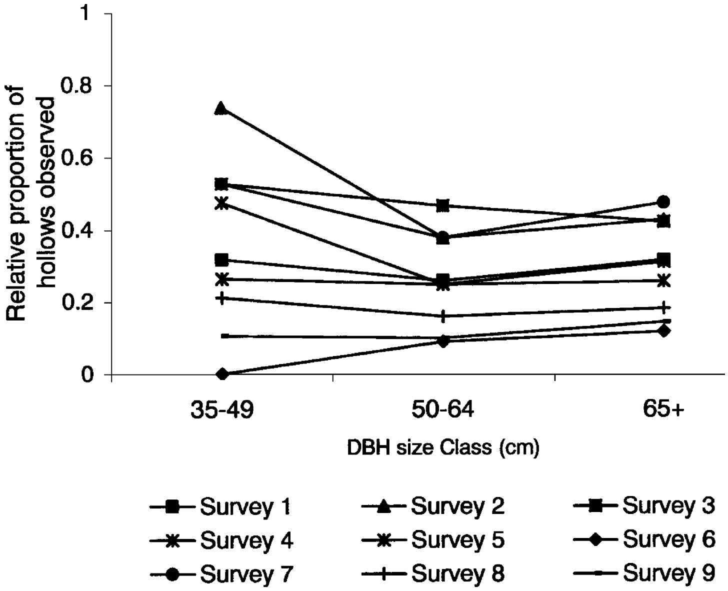

Fig. 1. The proportion of hollows recorded during ground-based surveys compared to the climbing survey for different size classes of trees. The size class 20–34 cm was excluded from this figure due to a lack of hollows.

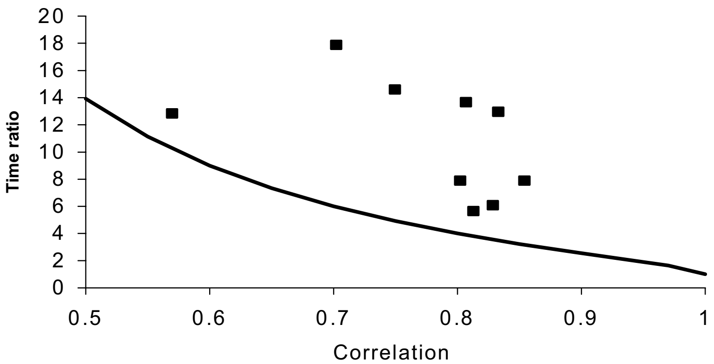

Fig. 2. Comparison of the efficiency of each ground-based visual survey with the critical ratio. The curved line represents the critical ratio. Points on the graph above the curved line indicate that double-sampling using ground-based visual survey is the more efficient measure of tree hollows, points below the line would indicate that climbing the trees is more efficient. The greater the distance from the critical ratio line the greater the level of efficiency for each survey.

4. Discussion

The accuracy of ground-based observations may be analysed on two levels; namely, the ability to accurately survey the number of hollows per tree and the ability to correctly identify hollow-bearing trees. Given that not all hollows are suitable for occupancy by arboreal fauna (e.g., Gibbons et al., 2002 found that only 43% of hollows showed signs of prior occupancy) are absolute counts necessary? Current forest management prescriptions generally aim to preserve a quota of hollow-bearing trees per unit area (e.g. Tanton, 1994). The selection of hollow-bearing trees for retention is based on a variety of factors in addition to the absolute number of hollows a tree contains. These include the spatial configuration of hollow-bearing trees over a given area, age of the trees, structural characteristics, health of the tree, and the crown size.

For this purpose, rapid ground-based surveys that accurately determine the presence or absence of hollows in trees may suffice. However, absolute counts will increase the probability of locating hollows suitable for occupancy by fauna because trees with multiple hollows are more likely to contain some suitable hollows (Gibbons et al., 2002).

In this study, ground surveyors were generally able to identify hollow-bearing trees; 82% of trees classified as being hollow-bearing and 89% of trees identified as not containing hollows were classified correctly (Table 1). With respect to the GLMM constructed to estimate the probability of hollow occurrence, only one ground survey (#6) varied significantly from the model constructed from pooled data (Table 2). The conservative nature of ground observations increases the likelihood that when a tree is classified as hollow-bearing, it tends to be correct. Therefore, solutions aimed at increasing the accuracy of classifying whether trees are hollow-bearing or not may need to overcome the conservative nature of the ground surveys. Statistical models of hollow occurrence based on characteristics of the tree (i.e. DBH, tree height) may be especially useful in this regard (Whitford and Williams, 2001; Fan et al., 2002).

In contrast there was less agreement between ground-surveys in estimates of absolute hollow frequency (Table 3). With respect to the GLMM constructed to estimate the absolute abundance of hollows, five out of nine surveys varied significantly from the model constructed from pooled data (Table 4). This result highlights the need for a standardised ground-based survey technique for assessing hollow frequency that increases the precision of ground-based observations and is generally applicable to a variety of forest types.

Financial and time constraints often require environmental managers to trade-off between taking more time or spending more money per measurement to make a few accurate measurements: or using the same total amount of time or money to make a greater number of measurements that are less accurate. The optimal strategy will be the one that provides the most precise and least biased estimate for a given budget. Double-sampling theory can be used to address this trade-off (Gilbert, 1987). In order to undertake a survey of hollow frequency in a forest the first step is to measure the relative efficiency of the more accurate but time consuming method (i.e. climbing-based surveys) and the less accurate but quicker method (i.e. ground-based surveys). This is achieved by selecting a random sample of trees that fall within predetermined DBH size classes that are representative of the forest patch (with sufficient replication). The more accurate method is used to undertake a survey of hollow frequency and the efficiency of the survey is compared to a ground-based survey on the same trees using the double-sampling equation (Eq. (1)) (Gilbert, 1987). If the less accurate but quicker method is more efficient, then the remainder of the survey should include this method. Bias in the ground-based estimates of hollow frequency can be overcome by determining the ratio of hollows seen using the less accurate method to hollows seen using the more accurate method. In this paper, the ground-based assessments of all the surveyors were sufficiently strongly correlated with the climbing assessments (Table 3) such that ground surveys with intermittent climbing surveys to correct for bias would be the most efficient method for conducting surveys of hollows in this forest type.

Periodic ongoing climbing assessments should be undertaken to check that the bias in ground-based surveys remains constant. Gilbert (1987) provides formulae for determining the proportion of samples that should be assessed accurately in a double-sampling scheme. Re-arrangement of the formulae (Gilbert, 1987) demonstrates that the proportion of trees that should be assessed with the accurate method to obtain the most precise estimate is equal to

$$f_0 = \left[\frac{(1-\rho)^2}{\rho^2 R}\right]^{0.5},$$

where ρ is the correlation between the two methods and R the ratio of costs for the accurate method relative to the inaccurate method. The actual number of trees that need to climbed when using the double-sampling method is likely to be determined by both the heterogeneity of the trees and environment. Based on the sample of surveyors in this study, this value ranged from 0.13 to 0.26 (i.e. one tree in every four to eight should be assessed by climbing).

The results of this study suggest that the level of experience of the ground surveyors is positively related to their ability to find hollows (Spearman's $r^2 = 0.52$), however, regardless of experience ground surveyors who take more time with their survey find a greater proportion of hollows (Spearman's $r^2 = 0.72$). The increased time taken to find additional hollows decreased the efficiency of the surveys to the point where the ratio of time taken for surveys approached the critical ratio (Fig. 2). Therefore, if double-sampling is to be employed, it may be necessary to set time limits for hollow assessments to ensure that double-sampling remains the most time-efficient option.

The approximate linear underestimation of hollow frequency displayed by ground-based surveys in relation to tree size classes (Fig. 1) enables the application of a simple correction factor to correct for bias (Table 3). The results of ground-based surveys can, therefore, be adjusted to more closely match those of climbing-based direct inspection. The variation in the proportion of hollows detected among ground surveyors means that such a correction factor must be surveyor-specific. A series of correction factors for different size classes of tree (or non-linear regression) would be required if the proportions of hollows identified from the ground varied with the size of the tree.

Although this study is based on just one species of tree (*E. leucoxylon*) in one type of vegetation community (open woodland), the factors that make hollows in trees difficult to assess using ground-based surveys (see introduction) exist in all vegetation types. As such, the general findings of this study regarding methodologies for the survey of tree hollows are expected to be applicable in the majority of woodlands and forest types around the world. Correlations between ground and climbing surveys obtained in this study (Table 3) tended to be greater than those from previous studies that relate counts from the ground with those obtained after felling of trees (i.e. $r = 0.57$: Whitford, 2001). It is possible that both tree and site characteristics may account for differences between our study and previous studies (e.g. Whitford, 2001). However, in surveys of felled stems, if a high number of hollows are contained within the canopy many will be lost due to mechanical damage when the tree is felled. The benefit gained through the use of non-destructive climbing surveys, in comparison with surveys of felled trees, will therefore increase in trees that contain a higher proportion of hollows within the canopy. The percentage of hollows occurring in the canopy for this study (92%) is similar to that found in a previous study of hollow occurrence in river red gum (*Eucalyptus camaldulensis*) in a similar open woodland environment (91%) (Newton-John, 1992).

In this study, the time taken for ground-surveys of small trees (DBH 20–40 cm) was usually less than 3 min. Quick assessments of the smaller trees within the sample may indicate a preconceived notion by the observer that hollows do not often occur in small trees, potentially biasing the ground-based surveys. Although a strong correlation has often been shown between the number of hollows within a tree and its diameter (Mackowski, 1984; Wormington and Lamb, 1999; Lindenmayer et al., 2000; Gibbons et al., 2001; Fan et al., 2002), it is important to note that many of the causes of hollow formation are strongly related to chance. Provided sufficient livewood to deadwood ratios can be maintained (Mattheck et al., 1995), hollows may occur in trees of limited diameter if the trees have been significantly weakened by natural or human-induced processes (i.e. repeated fire scarring, frequent branch damage). It follows that ground observers familiar with the dynamics of hollow formation may be more likely to conduct thorough surveys of smaller trees. Given this, it is not unreasonable to assume that bias may not only be reduced through experience but also through education.

The results of our research suggest that ground-based surveys using the double-sampling method will allow more efficient inventories of the occurrence of hollows in forests. The compilation of an accurate inventory of hollow resources will allow forest managers to make well-founded rational decisions pertaining to the retention of hollow-bearing trees, resulting in enhanced conservation prospects for hollow-dependent fauna. The various errors in the assessment of hollow-bearing trees suggest that a risk-based approach to the retention of hollows may be appropriate. This would be especially possible where statistical models for the occurrence or number of hollows already exists (e.g. Lindenmayer et al., 1991, 1993; Bennett et al., 1994). For example, where hollow-bearing trees are rare and all that currently exist should be retained, the chance of felling a hollow-bearing tree could be weighed against the economic cost of its retention. In other areas where there is a requirement to retain a certain number of hollow-bearing trees, the chance of not achieving this goal could be calculated. The economic cost to provide artificial hollows, such as nest boxes, can also be weighed against the cost of identifying and retaining existing hollows, and the habitat quality of artificial hollows compared to natural hollows.

Ground-based surveyors identified at most 44% of the total hollows (Table 2). However, the low proportion of hollows identified does not rule out ground-based observations as an important survey method if it can be shown that they are efficient when applied as part of a double-sampling strategy that can correct the bias.

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