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RESEARCH ARTICLE

Drone-based surveys improve estimates of tree hollow abundance and accessibility

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Abstract

1. Tree hollows are critical habitat for many species globally, and fauna studies often include assessments of hollow abundance. However, traditional ground-based surveys for hollows can be inaccurate, either over- or under-estimating hollow abundance and/or accessibility. In order to address this inaccuracy, ground-based hollow counts have previously been calibrated using a 'double-sampling' method such as felling or climbing trees. Here we test whether drone-based surveys can be used to count and assess tree hollow accessibility and discuss the considerations and limitations of using drones for hollow surveys.
2. In this study, we describe a survey of tree hollows in 134 *Eucalyptus* and *Corymbia* trees in a tropical savanna south of Darwin, Australia. Tree hollows were first counted from the ground using binoculars, then double-sampled using drone-based surveys.
3. Drone-based surveys detected more hollows than ground-based surveys, with the latter underestimating potential habitat hollows by at least 15%. Hollows with estimated entrance diameters of 5–10 cm and 10–20 cm were most likely to be missed by ground-based surveys. Drone-based surveys also provided more information on hollow accessibility, identifying that 38% of hollows were inaccessible to fauna due to being 'blind' or blocked by termite material.
4. *Practical implication*. Drone-based surveys potentially offer a more accurate method by which to count and assess tree hollow accessibility for fauna, as well as a less biased means of calibrating ground-based hollow counts. Important considerations for drone-based hollow surveys include weather restrictions (e.g. wind and rain), time available, vegetation density and potential impacts on wildlife. Where complete hollow surveys by drone are not possible or there is insufficient time available, we recommend that a subset of ground-surveyed trees are double-sampled using drone-based hollow surveys—particularly for studies where small- to medium-sized hollows are important. Ground-based hollow surveys alone risk underestimating the abundance of an important habitat resource and overestimating the number of currently accessible hollows. Thus, using a

more accurate method such as drone-based surveys to count or calibrate hollow numbers will likely provide improved estimates of landscape-scale hollow abundance and accessibility.

KEYWORDS
drones, habitat, hollow abundance, hollow accessibility, termites, tree hollows

1 | INTRODUCTION

Tree hollows form critical habitat for fauna (Gibbons & Lindenmayer, 2002; Newton, 1994). Many species rely on hollows for purposes such as shelter and breeding, and if there are not enough of these resources in the landscape, this negatively affects the ability of populations to persist in an area (Gibbons & Lindenmayer, 2002; Newton, 1994; Smith & Lindenmayer, 1988; Woinarski et al., 2011). In addition, species may prefer to only use hollows of certain sizes (Goldingay, 2009, 2011). It is therefore essential to be able to accurately quantify the number and size of hollows across the landscape: accurately quantifying hollow density will improve habitat suitability assessments and thus better inform management and conservation efforts.

The simplest and most common method by which to quantify tree hollows is by ground-based surveys of trees using binoculars. This method involves observing the tree from all sides and recording the number and size of tree hollows. However, ground-based counts can over- or underestimate the abundance of tree hollows and whether they are accessible (i.e. have a useable cavity) for fauna (Gibbons & Lindenmayer, 2002; Harper et al., 2004; Koch, 2008; Penton et al., 2020a; Rayner et al., 2011; Stojanovic et al., 2012; Woolley et al., 2018), resulting in inaccurate counts that might be extrapolated to landscape-scale hollow density estimates. Hollow abundance can be underestimated because not all hollows are visible from the ground (Gibbons & Lindenmayer, 2002), or overestimated if ground-observed hollows are 'blind' (Gibbons & Lindenmayer, 2002) or blocked by termite material (Penton et al., 2020a). Blind hollows occur when snapped branches or other forms of damage appear to be hollows from the ground, but no cavity is present (Gibbons & Lindenmayer, 2002). Termite material may temporarily block hollows so that they cannot be used by fauna (Penton et al., 2020a), but hollows can also become accessible once the termite material is cleared (Mackowski, 1984), and fauna such as birds can also excavate the material and nest in the cavity (Hindwood, 1959). Hollows that are blind or blocked by termites lack useable cavities and so are inaccessible to fauna. In order to improve hollow estimates, ground-based counts can be calibrated using a double-sampling method on a subset of trees, such as studying felled trees (Koch, 2008; Woolley et al., 2018) or climbing (Harper et al., 2004; Penton et al., 2020a; Stojanovic et al., 2012; Woolley et al., 2018). Rates of over- or underestimation from double-sampled trees can then be applied to broader estimates of hollow abundance and accessibility in the landscape.

Studying felled trees has been used on several occasions to calibrate hollow counts (Gibbons et al., 2000; Koch, 2008; Woolley et al., 2018). Once the tree has been surveyed for hollows using the ground-based method, the tree is then felled (either deliberately for research or as a part of planned forestry operations) and the number of hollows directly counted. Aside from the negative ecological implications of removing an important habitat resource, tree felling has the additional disadvantage of destroying smaller branch hollows (Koch, 2008), meaning that the method is not suitable for double-sampling small hollows. Tree climbing is a less destructive calibration method than felling, yet has its own limitations.

A major limitation of using tree climbing to double-sample trees is that not all trees are safe to climb (e.g. they are dead or structurally unsound), nor can all limbs be climbed and checked for hollows—especially the smaller and sometimes dead peripheral limbs (Penton et al., 2020a; Rayner et al., 2011; Woinarski & Westaway, 2008; Woolley et al., 2018). Dead trees and limbs often hold the most hollows (Gibbons & Lindenmayer, 2002; Koch, 2008), meaning that climbing has limited effectiveness when double-sampling many hollows. Ladders have also been used to survey tree hollows; however, they can be considered more limiting than climbing as many hollows cannot be safely accessed using ladders (e.g. Griffiths et al., 2018).

One potential alternative method by which to count hollows and calibrate ground-based hollow counts is the use of a drone to perform aerial surveys of trees. Drones have previously been used to detect wildlife using thermal imagery (e.g. Witt et al., 2020), and habitat quality using multispectral sensors (e.g. Wagner et al., 2021). While there have been no previously published studies using drones to visually count and assess the accessibility of tree hollows, this technology has the potential to successfully detect hollows and thus improve habitat suitability assessments for arboreal fauna. Surveying for hollows using a drone is non-destructive to the trees and avoids the sampling bias associated with tree felling or climbing. As drone-based surveys can detect peripheral hollows on smaller and/or dead limbs, this may make them more effective than the alternatives and thus reduces the calibration bias against smaller hollows. Finally, while specialist drone training and licencing may be required (depending on local legislation) and drone equipment will need to be purchased, drones are a multi-purpose resource that can be used for other research applications (such as in photogrammetry).

We hypothesised that drones would be a useful method for hollow surveys and tested this hypothesis through the following objectives:

1. To determine whether drones can be used to count hollow entrances of different sizes and assess hollow accessibility for fauna;
2. To compare drone-based hollow counts with ground-based counts; and,
3. To evaluate the use of drones for hollow surveys.

This study was located in an Australian tropical savanna: a biome that has had relatively few hollow abundance assessments compared to the temperate regions of Australia (Woolley et al., 2018). Due to the extensive distribution of tropical savannas across the northern third of Australia (Fox et al., 2001; Figure 1) and ongoing mammal declines in this region (Davies et al., 2018; Woinarski et al., 2011), it is important to have reliable methods for estimating the abundance and accessibility of critical habitat resources in this biome. Drone-based hollow surveys present an opportunity to improve the accuracy of habitat assessments.

2 | MATERIALS AND METHODS

2.1 | Study area and design

The study area was located at a long-term fire experiment site featuring 18 × 1 ha plots (see details in Levick et al., 2019) at the Territory Wildlife Park in Berry Springs (−12.70, 131.00), approximately 40 km south of Darwin, Australia (Figure 1). The vegetation in the area is tropical savanna, with a canopy dominated by *Eucalyptus miniata* A.Cunn. ex Shauer, *Eucalyptus tetrodonta* F.Muell. and *Corymbia bleeseri* (Blakely) K.D.Hill & L.A.S.Johnson (maximum height range 20–26 m, Levick et al., 2019), a shrubby midstorey and grassy understorey. The wet-dry tropical climate has a mean annual rainfall of ~1700 mm (Bureau of Meteorology, 2024), which predominantly occurs in the wet season from November to April (Richards et al., 2012). The average minimum and maximum temperatures are 22.0 and 34.4°C, respectively (Bureau of Meteorology, 2024).

FIGURE 1 Study area map. The field site was located approximately 40 km south of Darwin, Australia, and features 18 × 1 ha long-term experimental plots. Grey shading in the inset map represents the extent of tropical savannas (Fox et al., 2001).

2.2 | Ground-based tree and hollow surveys

In February and March 2022, we surveyed 134 trees across the 18 × 1 ha plots. We measured each tree for diameter at breast height (DBH, at 1.3 m) and counted the number of hollows from the ground using binoculars. Trees were selected using stratified random sampling of existing tagged and monitored trees to ensure balanced sampling of tree species and sizes across the experiment. Only individual trees of three species (*E. miniata*, $n = 53$; *E. tetrodonta*, $n = 46$; *C. bleeseri*, $n = 35$) with a DBH ≥20 cm were surveyed, as previous research suggests that these are most likely to exhibit hollowing (Braithwaite et al., 1985; Woinarski & Westaway, 2008; Woolley et al., 2018). Each tree was surveyed for hollows for a minimum of 2 min (Penton et al., 2020a): 30 s each at four opposing vantage points around the tree. Following Woolley et al. (2018), hollows were defined as cavities that may have a depth greater than the minimum entrance diameter. The minimum hollow entrance diameter was visually estimated and categorised into three classes (5–10 cm, 10–20 cm and >20 cm). The proportion of the hollow entrance that was visibly blocked by termite material was also visually estimated and recorded. All hollow surveys were conducted by one surveyor (E. Rochelmeyer).

2.3 | Drone-based hollow surveys

Over a total of 15 days in April and June 2022, a commercially available DJI Mavic 3 drone (with an RC Pro Controller; Figure S1a) was used to 'double-sample' the 134 ground-surveyed trees for hollows (i.e. drone-based surveys were conducted after ground-based surveys). This drone was selected as it can capture high-resolution photos (12–20 megapixels), is small enough (dimensions 34.8 × 28.3 × 10.8 cm) to carefully manoeuvre under and between tree canopies (e.g. as close as 1 m to branches) and has up to 28× zoom, which can be viewed via live feed on the controller (DJI, 2022). These characteristics enabled the close viewing of hollows in less accessible parts of the tree, while also maintaining distance from moving branches. The RC Pro Controller has a bright display (1000 cd m^{-2}) with 1920 × 1080-pixel resolution (DJI, 2022), which was better for viewing hollows than phone or tablet displays, especially in bright sunlight. The drone was equipped with propeller guards to protect the propellers from close vegetation.

Due to the low propeller clearance of the Mavic 3, a firm landing pad was also required for landing in dense grassy areas and uneven terrain. The landing pad was custom-made from MDF (medium-density fibreboard) with an attached shoulder strap and overlaid with a purchased orange landing circle (Figure S1c). Six spare batteries and a car charger were required to maximise work throughout the day by charging flat batteries whilst others were in use. A second person assisted with carrying the equipment, acting as a spotter (to watch out for any hazards to the drone or to people), keeping time and recording hollow observations.

Drone-based hollow surveys were conducted by the same researcher (*E. Rochelmeyer*) as ground-based surveys. Each tree was surveyed for hollows for a minimum of 8 min: 2 min at four opposing vantage points around the tree. This timing was chosen as a standardised minimum survey time after trialling drone-based hollow surveys prior to beginning the study, as 8 min generally provided sufficient time to completely survey most trees for hollows, and also assess hollow accessibility. Where not all branches could be surveyed in the 8 min time frame (e.g. due to complex canopies and difficulties manoeuvring), additional time was added until all branches were surveyed, and this extra time was noted. Some trees such as small young trees were quick to survey, and while each side was surveyed for a minimum of 2 min, the shorter time taken to finish all branches was noted.

As with ground-based surveys, hollow location and size class were visually estimated for each tree, as well as the proportion of the hollow entrance that was visibly blocked by termite material. Whether each entrance had sufficient estimated depth to be deemed a hollow was also noted (hollows with sufficient depth were categorised as 'true' hollows). Sufficient hollow depth was defined as having a depth greater than the minimum entrance diameter (Woolley et al., 2018). Hollows without sufficient depth were either 'blind' (did not lead to a cavity) or blocked by termite material and thus categorised as inaccessible to fauna.

Permits to fly the drone were obtained from the Parks and Wildlife Commission of the Northern Territory (permits DABL22/381, DABL22/454, DABL22/689). A step-by-step protocol for drone-based hollow surveys and the equipment list is provided in the Supporting Information, along with supporting photographs in Figure S1.

2.4 | Data analysis

All data analyses were conducted in R (R Core Team, 2024). The ability of ground-based surveys to accurately detect the presence or absence of different hollow size classes in a tree was assessed using confusion matrices with the CARET R package (Kuhn, 2008). The drone-based survey observations were considered to be the reference state, assuming the drone-based surveys were accurate. Accurately observing whether a hollow *was not* present was equally important to observing whether a hollow *was* present. As such, balanced accuracy was used to interpret the confusion matrix results. Balanced accuracy represents the average of the true positive rate 'sensitivity' (i.e. how accurately hollows were observed as being present) and true negative rate 'specificity' (i.e. how accurately hollows were observed as being absent; Brodersen et al., 2010). The standard errors for the estimates of balanced accuracy were extracted from binomial generalised linear models.

3 | RESULTS

When counting and assessing tree hollows, drone-based surveys were able to detect hollows that were not visible from the ground, in areas unsafe to climb, or that were inaccessible to fauna. Examples of these include hollows that were upwards facing or obscured by branches, located on small and/or dead branches, or had termite material blocking their entrance (Figure 2).

In the 134 double-sampled trees, ground-based surveys detected a total of 465 hollows, whereas the drone-based surveys detected a total of 659 hollows (Table 1). Ground-based surveys detected that 3% of hollows were inaccessible to fauna (16 out of 465 ground-surveyed hollows were observed to be blocked by termite material; Table 1), whereas drone-based surveys detected that 38% of hollows were inaccessible (251 out of 659 drone-surveyed hollows were observed to be blocked by termite material or were blind; Table 1). Most ground-surveyed hollows were categorised as indeterminate, as ground-based surveys often could not verify whether hollows were true, blocked or blind. When considering potential habitat hollow numbers (the sum of true hollows and termite-blocked hollows which may become hollows once the termite material clears or is excavated), drone-based surveys detected 550 hollows compared to the 465 total hollows of the ground-based surveys, resulting in ground-based surveys underestimating potential hollows by at least 15% in these environments (Table 1).

The average number of hollows per tree increased with DBH size category, with *E. miniata* tending to have more hollows per tree than other species (Table 2).

Ground-based hollow surveys were considerably faster to undertake than drone-based surveys. When conducting ground-based

FIGURE 2 Photos of hollows captured by drone-based surveys, including examples of (a) an upwards-facing hollow, (b) a hollow obscured from view from the ground, (c and d) peripheral hollows on small and/or dead branches and (e and f) hollows blocked by termite material.

surveys, a maximum of 100 trees were surveyed in one day, whereas during the drone-based surveys, a maximum of 14 trees were surveyed in one day. Wind was the main limitation of drone survey efficiency. On average, drone-based surveys were able to assess three trees per hour (~20 min/tree), which included the time taken to move between trees in a plot and between survey points on a tree. When considering only the time taken to survey a tree, drone survey time increased with the DBH of the tree and the number of hollows present (Figure 3).

Across all estimated hollow size classes, the balanced accuracy of ground-based hollow counts was 80% compared to drone-based counts, with the largest error occurring due to false negatives (Figure 4). Hollows with estimated entrance diameters of 10–20 cm had the highest rate of false negatives, where ground-based surveys did not identify the presence of this hollow size in a tree, whereas drone-based surveys identified them as present. This was followed by hollows with estimated entrance diameters of 5–10 cm (Figure 4). For each estimated hollow size class, >20 cm hollows had the highest balanced accuracy (91%), whereas 5–10 cm hollows had the lowest balanced accuracy (62%), followed by 10–20 cm hollows (83%; Figure 4 and Table 3).

TABLE 1 Comparison of ground- and drone-based hollow survey numbers across the entire survey and the average per tree.

Survey method	Type	Count	Average count per tree (± SE)
Ground	**Total**	**465**	**3.5 (±0.2)**
	Indeterminate	449	3.4 (±0.2)
	Blocked hollows	16	0.1 (±0.0)
Drone	**Total**	**659**	**4.9 (±0.3)**
	True hollows	408	3.0 (±0.2)
	Blocked hollows	142	1.1 (±0.1)
	Blind hollows	109	0.8 (±0.1)

Note: Results are summarised as total hollow counts and separated into 'true hollows' (which have sufficient depth to be deemed a hollow), 'blocked hollows' (hollows blocked by termite material), 'blind hollows' (do not lead to a cavity) and 'indeterminate' (could not be verified as true, blocked or blind). Trees surveyed $n = 134$.

Abbreviation: SE, standard error.

The percentage of hollows in each estimated hollow size class (as detected by drone-based surveys) that were inaccessible to fauna due to being blind or blocked by termite material ($n = 251$) decreased as the hollow size class increased (Table 4). Hollows with estimated entrance diameters of 5–10 cm had the highest rate of inaccessibility (43%), closely followed by 10–20 cm hollows (33%). Hollows with estimated entrance diameters of >20 cm had the lowest rate of being either blind or blocked by termite material, with only 13% of hollows marked as inaccessible to fauna.

4 | DISCUSSION

This is the first published study to use drone-based surveys to visually count and assess tree hollow accessibility. When considering potential habitat hollow numbers—the sum of true hollows and termite-blocked hollows (which may become hollows once the termite material clears or is excavated by fauna)—our ground-based surveys underestimated the number of potential hollows by at least 15%, and this was largely due to ground-based surveys observing fewer hollows overall. Of all estimated hollow size classes, 10–20 cm hollows were most frequently missed by ground-based counts, followed by 5–10 cm hollows. The size of the hollow and position on the tree likely contributes to this variation in ability to observe hollows; however, we did not explicitly test this. For example, 10–20 cm hollows may have been the least observed due to upwards orientation or obscured visibility of this size class from the ground (e.g. Figure 2a,b). Smaller 5–10 cm hollows were potentially more visible on peripheral limbs, while >20 cm hollows may have been more obvious due to their large size. Indeed, >20 cm hollows were the most likely to be accurately identified as present or absent by ground-based surveys. In other vegetation types, large >20 cm hollows are also likely to be the most identifiable across different forest types due to their high visibility (e.g. Koch, 2008); however, the relative accuracy of 5–10 cm and 10–20 cm hollow observations may vary with growth form and tree species.

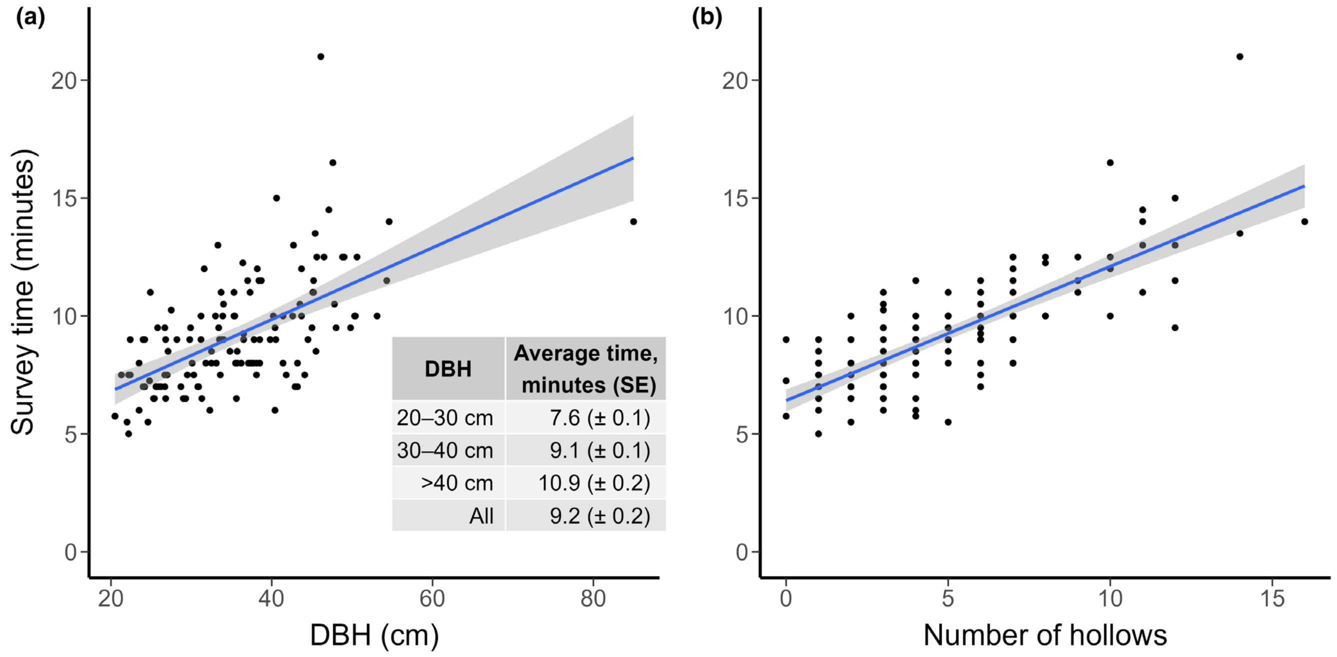
In addition to detecting more hollows, drone-based surveys provide more information on the accessibility of detected hollows for fauna. Drone-based surveys identified that 38% of hollows were inaccessible to fauna due to being blind or blocked by termite

TABLE 2 Comparison of average true hollow numbers per tree, by tree species and diameter at breast height (DBH) category.

DBH category	Average number of true hollows per tree (± SE)							
	All stems		20–30 cm		30–40 cm		>40 cm	
Species								
Corymbia bleeseri	2.8 (±0.4)	$n = 35$	1.9 (±0.3)	$n = 12$	2.4 (±0.9)	$n = 12$	4.1 (±0.8)	$n = 11$
Eucalyptus miniata	3.3 (±0.3)	$n = 53$	1.2 (±0.6)	$n = 13$	3.6 (±0.5)	$n = 23$	4.6 (±0.5)	$n = 17$
Eucalyptus tetrodonta	2.9 (±0.5)	$n = 46$	1.7 (±0.3)	$n = 14$	1.8 (±0.4)	$n = 18$	5.6 (±1.3)	$n = 14$
All species	3.0 (±0.2)	$n = 134$	1.6 (±0.2)	$n = 39$	2.7 (±0.3)	$n = 53$	4.8 (±0.5)	$n = 42$

Note: True hollows are those with sufficient depth to be deemed hollow (i.e. are not blind or blocked by termite material). Hollow numbers are from drone-based surveys.

Abbreviation: SE, standard error.



DBH	Average time, minutes (SE)
20–30 cm	7.6 (± 0.1)
30–40 cm	9.1 (± 0.1)
>40 cm	10.9 (± 0.2)
All	9.2 (± 0.2)

FIGURE 3 The influence of tree size and the number of hollows present on drone survey time: (a) survey time as related to the diameter at breast height (DBH, cm) of the tree and (b) survey time as related to the number of hollows in the tree. The inset table in (a) details the average time in minutes (± standard error, SE) to survey a tree by DBH size class and on average across all size classes. The lines were produced using a linear model, points represent original data, and shading represents 95% confidence intervals.

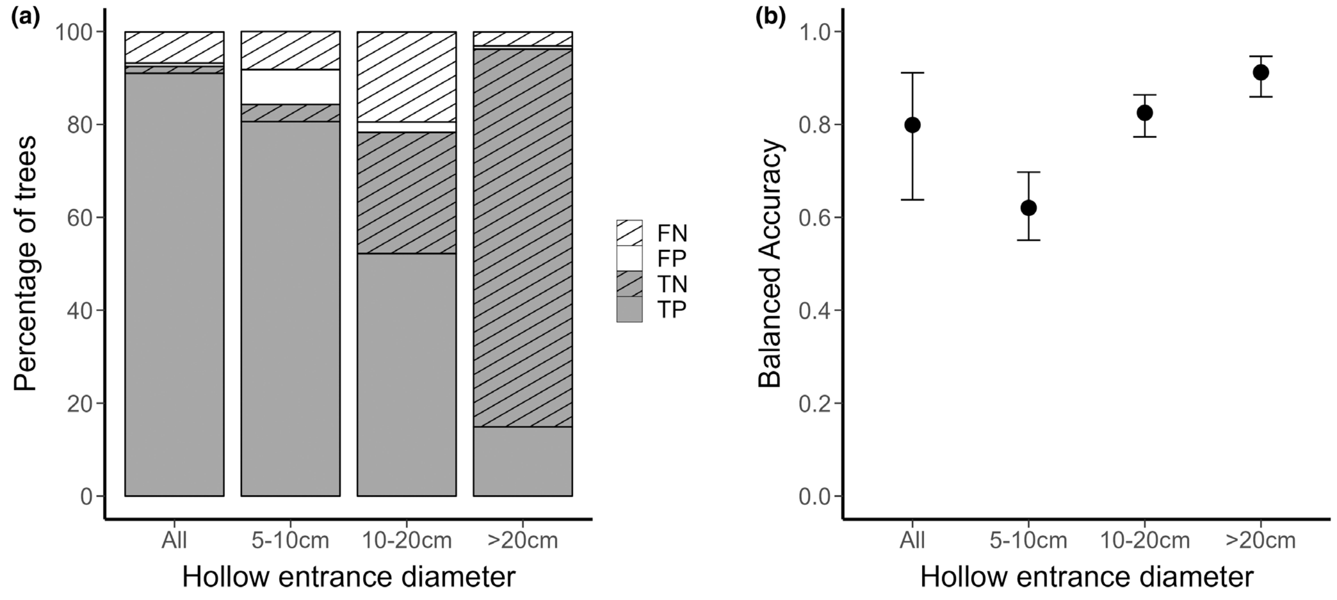


FIGURE 4 Results of confusion matrices on the presence or absence of different estimated hollow entrance diameter classes in a tree. Confusion matrices compared the results of ground-based hollow surveys to drone-based hollow surveys, with the latter treated as the reference: (a) the percentage of true and false observations for each estimated hollow entrance diameter class in a tree; FN, false negatives; FP, false positives; TN, true negatives; TP, true positives; (b) balanced accuracy values with standard errors for each estimated hollow entrance diameter class.

material (and so had insufficient depth to be deemed a hollow). In contrast, only 3% of hollows were identified as inaccessible by ground-based surveys, representing only those hollows that could be identified as being blocked by termite material. Whether hollows were blind could not be verified by ground-based surveys, and it is also likely that more hollows were blocked by termite material than could be identified from the ground. These drone-based survey accessibility results are similar to those of hollow surveys by Penton et al. (2020a) in the savannas of Melville Island, ~120 km north of our study site and dominated by the same tree species. Using climbing surveys to validate ground-based surveys, Penton et al. (2020a) observed that 44.5% of hollows were inaccessible to

TABLE 3 Metrics from confusion matrix analyses on the presence or absence of different estimated hollow size classes in a tree, as detected via ground-based surveys versus drone-based surveys (the reference).

	All hollows	5–10 cm hollows	10–20 cm hollows	>20 cm hollows
Accuracy	0.93	0.84	0.78	0.96
Sensitivity	0.93	0.91	0.73	0.83
Specificity	0.67	0.33	0.92	0.99
Balanced accuracy	0.80	0.62	0.83	0.91

TABLE 4 Comparison of inaccessible hollow numbers between different estimated hollow entrance diameter classes.

	All hollows	5–10 cm hollows	10–20 cm hollows	>20 cm hollows
Total hollows (*n*)	659	396	232	31
Hollows blocked by termite material % (*n*)	22% (142)	22% (89)	22% (50)	10% (3)
'Blind' hollows % (*n*)	17% (109)	20% (81)	12% (27)	3% (1)
Total inaccessible hollows (termite blocked + 'blind') % (*n*)	**38% (251)**	**43% (170)**	**33% (77)**	**13% (4)**

Note: Hollows inaccessible to fauna include those blocked by termite material or are 'blind' (i.e. do not lead to a cavity). Hollow numbers are from drone-based surveys.

fauna due to termite blockages. In our study, hollows with small to medium entrance diameters (5–10 cm and 10–20 cm) were most frequently inaccessible to fauna. While termite blockage is a major factor in our study due to the high termite activity of tropical savannas, this is unlikely to be an important consideration in locations where termites are not as abundant. In these locations, the identification of sufficient hollow depth (i.e. that hollows are not blind) is likely to be a more important factor when considering hollow abundance and accessibility for fauna.

4.1 | Method evaluation

The added accuracy and information provided by drone-based hollow surveys make a compelling case for the use of drones as an alternative and stand-alone method for counting and assessing the accessibility of tree hollows for fauna. Drone-based surveys could remove the requirement for double-sampling (until a more accurate hollow survey method is found) and consequently reduce time in the field compared to ground-based surveys where double-sampling is required to improve accuracy. While drone-based surveys do take longer than ground-based surveys, this could be offset by strategically targeting a smaller sample of trees which represents the tree species and size distribution in the landscape.

Drone-based surveys are also likely to minimise observer error in hollow surveys. For ground-based surveys, the accuracy of hollow counts is likely to be affected by the level of experience of surveyors and their ability to accurately observe and assess hollows. In contrast, drone-based surveys allow closer and clearer inspection of hollows, which can reduce the uncertainty in hollow assessments and thus the potential error due to different surveyors and their levels of experience.

Where complete hollow surveys by drone are not possible, drone-based surveys offer an improved alternative to previous hollow count double-sampling methods. Not only are drone-based surveys less destructive than tree felling, but they are also less biased against and better able to capture the small peripheral hollows that may be damaged or otherwise unobserved by felling or climbing (e.g. Koch, 2008; Penton et al., 2020a; Rayner et al., 2011; Woolley et al., 2018).

4.2 | Considerations and limitations

There are several considerations that influence timing and how many trees can be surveyed using a drone in a day. While in this study we used a minimum 2-min survey for each of the four vantage points around the tree—for a total of 8 min minimum survey time—this timing might be adjusted depending on the ecosystem hollowing rate and tree size. Bigger trees and those with more hollows generally take more time to survey (Figure 3). In this study, the smaller trees frequently took less than 8 min to completely assess (Figure 3a), and so future studies on smaller trees (<20 cm DBH) would likely only require 1-min surveys for each point around the tree. Having sufficient spare batteries and a car charger for re-charging spare batteries while continuing surveys is also of importance for maximising the number of trees that can be surveyed during a day within the optimal weather conditions for flying. In this study, wind speed was the main limiting factor that influenced the number of trees able to be surveyed in a day. Due to the precise and careful manoeuvring required to position the drone under and between the tree canopies, low- to no-wind conditions were optimal for safe flying. In addition, when using zoom to focus in on a hollow, small movements from wind are magnified in the live feed, making it difficult to clearly view and photograph hollows. When wind conditions were too fast for safe flying and the clear viewing of hollows, the surveys were stopped and the time recorded. These times coincided with wind speeds of approximately 11–13 km h^{-1} (Bureau of Meteorology, 2023), recorded at the closest weather station, approximately 13 km from the study site. In addition to wind speed, rain also limits the use of drones and so would restrict when drone surveys could be conducted. For example, the regular heavy monsoon rains of tropical Australia would limit the use of drones to the dry or transition seasons.

Sourcing a drone with sufficient zoom capabilities is also an important consideration for drone-based hollow surveys. A powerful zoom enables the pilot to clearly view hollows while maintaining a safe distance from tree limbs and moving canopies. The Mavic 3 drone used in our study had a powerful 28× zoom (refer to Figure S2 for an example of the zoom capability), and this enabled the operator to view hollows and maintain a distance of at least 1 m from the tree. In addition to the zoom capability, the maximum gimbal angle will affect which hollows can be viewed. While we were able to view all hollows visible from the ground using the drone in this study, at times the gimbal was tilted to the maximum angle (+35°; DJI, 2022) in order to view some hollows. Should hollows be on an angle greater than the gimbal range (i.e. sharp downwards-facing hollows), then drone-based observations may not be able to view inside the hollow to confirm accessibility for fauna. It is worth noting though that such hollows would likely be observed by the drone pilot who would be positioned adjacent to the tree. As the gimbal tilts to −90° (DJI, 2022), there was no issue with achieving the correct angle to view upwards-facing hollows, which would not be visible to ground-based surveys.

Studies using drones should also consider the potential negative impacts of drones on wildlife, given that they have the potential to disturb animals using tree hollows (Mo & Bonatakis, 2022) and can potentially injure birds that may collide with the drone (e.g. attacking raptors, flushing animals from hollows). Responsible drone-users should take precautions to minimise animal welfare impacts, including: not flying close to hollows known to be active (e.g. if fauna have been seen), avoiding peak times of activity (e.g. breeding season) and having a spotter keep watch for birds that are attracted to the drone (for more recommendations, see Mo & Bonatakis, 2022). Guidance by an animal ethics committee and formal animal ethics approval (weighing up the benefits of the survey against the potential negative impacts on animal welfare) should be sought prior to undertaking drone surveys for fauna. It is also important to check local legislation and policies governing the use of drones as well as any requirements (such as licences, permits and land permissions).

It is important to note that this study assumes that drone-based survey results are accurate; however, testing this accuracy would be subject to future research. As with ground-based surveys, drone-based surveys of hollows are still limited to visually estimating the size and depth of hollows and are prone to observer error. Developing a method to measure hollow dimensions through drone imagery would enable drone-based surveys to quantify hollow size and depth and improve the accuracy of this survey method.

While drone-based surveys of trees occurred at independent times to the ground-based surveys in this study, should double-sampling surveys occur immediately following the ground-based surveys on individual trees, this presents potential bias based on previous experience if the same observer conducts the surveys. To avoid this bias, future studies may consider having different observers conduct double-sampling surveys.

As this study was conducted in the relatively open savannas of northern Australia, future research could test the applicability and effectiveness of drone-based hollow surveys in less open vegetation, such as closed forests, where drone manoeuvrability is significantly reduced. In our study, tree densities were in the range of 750–5472 stems per hectare (Levick et al., 2019) and the cover of woody vegetation above 2 m ranged from 37% to 80% (Rochelmeyer et al., unpublished data). The denser plots in our study were more challenging and required careful and precise manual flying. As the drone was always flown in open savanna habitat and within visual line-of-sight with the pilot near the surveyed trees, we experienced no GPS or drone-to-controller connection issues; however, more closed and denser canopies may reduce GPS accuracy, which can restrict the navigation ability of the drone (as well as the ability of the pilot to maintain visual line-of-sight with the drone). Further work should be done to test the ability to safely fly drones in such contexts.

Finally, it is important to note that flying a drone within and around the canopy of trees (while also avoiding understorey vegetation) can be an intricate operation and requires specialist skills, including training, experience and fine-control for manual flying.

4.3 | Applications

The presence of suitable hollows is an important factor in habitat selection for many fauna (e.g. Goldingay, 2009, 2011; Penton et al., 2020b; Tidemann et al., 2010). Consequently, quantifying these resources can be useful in identifying valuable habitat (Gibbons & Lindenmayer, 2002) or predicting the impacts of changes in land management and use on fauna. Using ground-based hollow surveys alone risks underestimating potential habitat hollow abundance and habitat value of the landscape, and so a more accurate method such as drone-based surveys should be used to count hollows or calibrate hollow numbers. This is particularly true for small-to-medium-sized hollows (estimated entrance diameters 5–10 cm and 10–20 cm, respectively). As shown in this study, these hollows are more likely to be missed by ground-based counts as well as by studying felled or fallen trees (Koch, 2008) and by tree climbing surveys (Penton et al., 2020a; Rayner et al., 2011; Woinarski & Westaway, 2008; Woolley et al., 2018). Such small- to medium-sized hollows are important habitat for many savanna fauna species, including the threatened Gouldian finch *Erythrura gouldiae* (Goldingay, 2009; Tidemann et al., 2010), black-footed tree-rat *Mesembriomys gouldii* and brush-tailed rabbit-rat *Conilurus penicillatus* (Penton et al., 2020b). As such, assessments of habitat condition and surveys for such fauna should include a more accurate hollow survey method such as drone-based surveys.

In addition, models of hollow occurrence and abundance in the landscape are often built from relationships between field-observed hollows and tree structural characteristics such as DBH, canopy height and crown cover (e.g. Owers et al., 2014; Zlonis et al., 2021). Should such models be solely built from ground-based hollow observations, the error rate from ground-based surveys would likely be propagated to landscape-scale hollow estimates. Future research should test the effects of such errors on hollow abundance models at larger scales and investigate the ability of drone-based surveys to calibrate hollow estimates.

5 | CONCLUSIONS

In the future, drone-based surveys could offer an accurate method by which to count and assess tree hollow accessibility for fauna, as well as a less biased means of calibrating ground-based hollow counts. When using drones to survey for tree hollows, it is important to consider potential restrictions due to weather and vegetation density, the time available for surveys, potential impacts to wildlife and any legal restrictions, licence requirements and land permissions to pilot drones. This research was conducted in the relatively open savannas of northern Australia, and future research could investigate the use of drones for hollow surveys in other vegetation types. Where complete hollow surveys by drone are not possible or there is insufficient time available, we recommend that a subset of ground-surveyed trees are double-sampled using drone-based hollow surveys—particularly for studies where estimating abundance of small-to-medium-sized hollows is important. Without using a more accurate method to survey for tree hollows, ground-based hollow surveys alone risk underestimating the abundance of a critically important habitat resource at patch and landscape scales.

AUTHOR CONTRIBUTIONS

Ellen Rochelmeyer conceived the ideas and designed the methodology with support from all other authors; Ellen Rochelmeyer collected the data; Ellen Rochelmeyer analysed the data with support from all other authors; Ellen Rochelmeyer led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1002/2688-8319.70007.

DATA AVAILABILITY STATEMENT

Data available from the CSIRO Data Access Portal https://data.csiro.au/collection/csiro:61536 (Rochelmeyer et al., 2024).

RELEVANT GREY LITERATURE

You can find related grey literature on the topics below on Applied Ecology Resources: Drones, Habitat, Tree hollows.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1. Photos of drone equipment and methodology. (a) RC Pro Controller with a bright display for viewing hollows, (b) photographing tree ID prior to flight to identify subsequent photos of tree and hollows, (c) custom-made firm landing pad with MDF (medium-density fibreboard) base, shoulder strap and landing circle and (d) working in dense vegetation requires careful manual flying to take off, manoeuvre and land.

Figure S2. Example photos of drone zoom capability. (a) Position of drone relative to the tree (~15 m), (b) tree viewed without zoom from drone position (hollow circled in yellow) and (c) hollow viewed using maximum zoom (28×) from drone position.

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