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Field methods to identify Palm Cockatoo nest hollows

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Abstract. Within Australia, the iconic Palm Cockatoo *Probosciger arterrimus macgillivrayi* occurs only on the Cape York Peninsula, Queensland, has recently been listed as Endangered, and requires large, old hollow-bearing trees for nesting. Surveys for these trees are crucial for management purposes. Typical surveys rely on following auditory (vocalisations) and visual (sightings) cues to determine the presence of birds or nests. However, nesting hollows can easily be inadvertently overlooked during such surveys because of false absences caused by biennial nesting, decreased vocal activity during nesting, and silent flushing from active nests when approached. We developed a systematic, grid-based transect methodology that maximises the likelihood of identifying potential, used, and confirmed Palm Cockatoo nest hollows and this has been implemented on western Cape York Peninsula since 2015. This method does not rely on bird presence at the time of surveys, but instead relies on multiple, specific signs of recent Palm Cockatoo nesting activity, to the exclusion of other large, sympatric parrots. We tested this method on novice observers and found that it enabled them to rapidly learn how to detect Palm Cockatoo hollows in the landscape. Thus, for ecological surveys on Cape York Peninsula, we propose that this method should supersede previous auditory/visual surveys to identify Palm Cockatoo nesting sites, and we hope that this improves the conservation of this species in Australia.

Introduction

Parrots (Psittaciformes) are one of the most endangered orders of birds globally, with almost one third of extant species at some level of extinction threat (Critically Endangered, Endangered or Vulnerable: IUCN 2018). Particularly vulnerable are large parrots with long generation times and small geographical ranges (Heinsohn *et al.* 2009; Olah *et al.* 2016, 2018). Many parrots nest in hollows and are therefore dependent on forests that include old trees, leading to increased vulnerability to climate change, land-use change or altered land-management regimes (Murphy & Legge 2007; Reside *et al.* 2012).

The Palm Cockatoo *Probosciger arterrimus* is a large, black, tropical-dwelling parrot species distributed across lowland New Guinea and the Cape York Peninsula in northern Australia (Parr & Juniper 2010). It is renowned for its unique drumming behaviour, whereby males in some populations on Cape York Peninsula use a crafted stick or seed pod to repeatedly strike a branch or tree hollow in an individualistic drumming style (Heinsohn *et al.* 2017). Palm Cockatoos have a slow life history, characterised by a long life-span, low fecundity, and low breeding success (Murphy *et al.* 2003; Heinsohn *et al.* 2009). In addition, infrequent clutches (a single egg per 2.2 years on average), high infertility (low egg hatch rate) and high predation pre-fledging (Taylor 2000; Murphy *et al.* 2003) render Palm Cockatoos particularly susceptible to external pressures (Bennett & Owens 1997; Olah *et al.* 2016).

A recent population viability analysis that used new data on population connectivity (via genetics and vocal dialects) determined Australian Palm Cockatoos *P. a. macgillivrayi* to be in severe decline in eastern and northern Cape York Peninsula (Keighley *et al.* 2021). The Palm Cockatoo was subsequently elevated to Endangered under the Queensland *Nature Conservation Act 1992* on 10 November 2021. It is considered endangered under the 2020 Action Plan for Australian Birds (Heinsohn *et al.* 2021). Consequently, proposed changes to land use and associated development approval processes require that special consideration be given to Palm Cockatoos and their habitat.

As obligate hollow-nesters, the density of tree hollows in the landscape determines the possible breeding density of Palm Cockatoos (Murphy 2005), and large-hollowed trees required for nesting may take >250 years to form (Woinarski & Westaway 2008). Nesting hollows are not the only habitat required for Palm Cockatoo breeding. Mating pairs actively maintain and defend multiple hollows during the breeding season and pairs have been observed defending between four and 12 hollows annually (Wood 1988; Murphy *et al.* 2003). Although these hollows may not be nests, they may be used as such in future seasons (Murphy *et al.* 2003). They are also significant sites for display during courtship (‘display hollows’), which is an essential ritual for pair-bonding. Thus, display hollows also require identification and protection.

Current methods to identify breeding habitat and detect Palm Cockatoo hollows are not standardised, systematic or reliable, and rely on auditory and visual confirmation to locate breeding habitat, which requires both bird presence and a substantial amount of observer effort (Murphy *et al.* 2003; Zdenek *et al.* 2015; Heinsohn *et al.* 2017; Keighley *et al.* 2017). Gradual and continuing land-use changes on Cape York Peninsula, such as grazing, mining and altered fire regimes, all cause a loss of nesting hollows, which is the greatest threat to Palm Cockatoos (Threatened Species Scientific Committee 2015), making the need for effective field surveys for the species vitally important. To address these shortfalls and improve the management and conservation of Palm Cockatoos, we have developed a method to locate and identify hollows used by Palm Cockatoos. This method incorporates systematic, grid-based field transects to actively search for and identify the highest number of potential hollows as possible. Hollows are then categorised based on standardised criteria drawn from acquired knowledge from field studies, including substantial behavioural observations. Importantly, this method does not rely on the active presence of birds, making it robust against false absences caused by daily fluctuations in Palm Cockatoo presence, their biennial nesting (every other year: Murphy *et al.* 2003), and their silent flushing from active nests when approached. For land-use and conservation surveys, we propose that this method should supersede previous auditory/visual surveys to identify Palm Cockatoo breeding areas.

Recommendations to identify hollows used by Palm Cockatoos

Systematic survey

From 2013 to 2015, we progressively developed and trialled a systematic method to search for and identify Palm Cockatoo hollows before land clearing. After trialling many different iterations of the method over the years, we conclude this step-by-step method (Figure 1) to be the most effective means to accurately identify Palm Cockatoo nests and hollows.

Conducting at least two surveys in July–December is recommended so that early- or late-breeding pairs are not missed in surveys and so that recent fire does not increase false absences by removing ground signs of nesting. The workflow for systematic surveys of Palm Cockatoo breeding habitat is as follows:

1. Use aerial maps to narrow down the search area for potential Palm Cockatoo breeding habitat. Where surveys are undertaken in *Eucalyptus* woodland, a maximum of 2 km from rainforest/gallery forest edges will provide a conservative distance from recommendations in Murphy *et al.* (2003).
2. Use GIS software to generate digital parallel survey lines (in any suitable orientation) and upload to GPS devices. The chosen transect separation interval (typically 100 m) is based primarily upon the distance off the transect centreline at which potential nesting hollows can reliably be seen (i.e. 50 m) when walking at ground level through Darwin Stringybark *Eucalyptus tetrodonta* open forest, although denser vegetation types may require closer transect lines.
3. Train observers in signs of Palm Cockatoo activity, (Table 1, Figures 2–4) and explain aspects of hollows that preclude use by Palm Cockatoos (see ‘Signs to identify Palm Cockatoo hollows’ section below).
4. Pairs of observers are recommended for safety and efficiency. The navigator leads using the handheld GPS, identifies trip hazards, and looks for hollows where possible. The surveyor sets the speed and is primarily responsible for detection of hollows, which, depending on the orientation of the sun, may require circling trees of interest to avoid being backlit and to view hollows that are visible from only one angle.

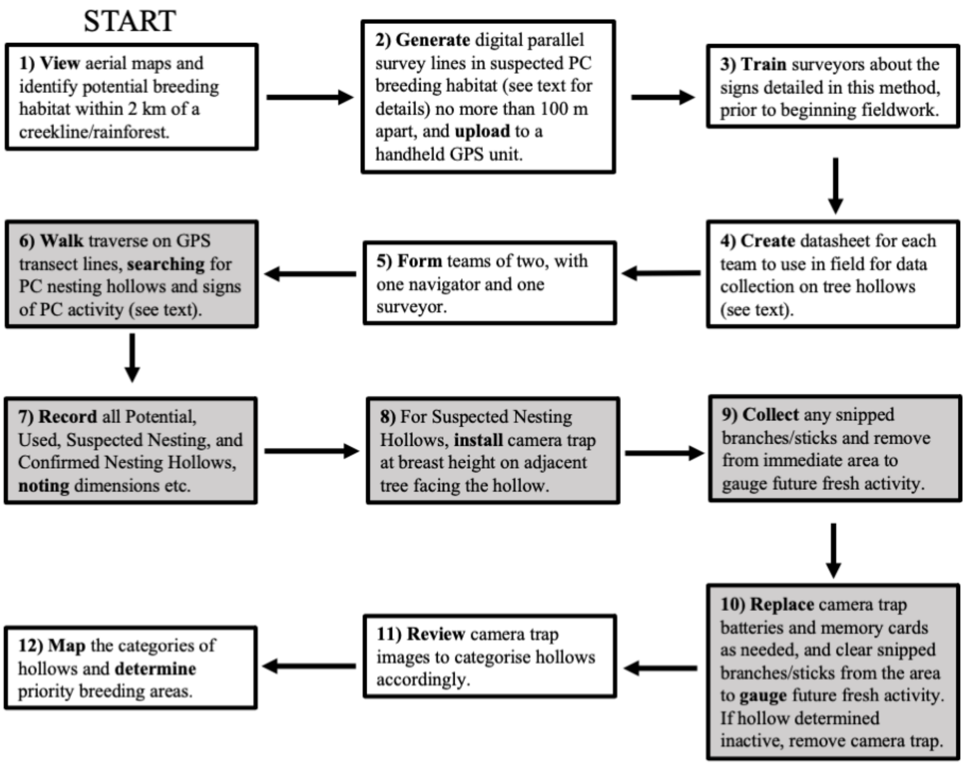

Figure 1. Systematic survey flow-chart to locate and identify hollows used by Palm Cockatoos for breeding. Start at top left box. White boxes indicate office work. Grey boxes indicate collection of field data. PC = Palm Cockatoo. See text for additional details.

Table 1. Evidence and likelihood of Palm Cockatoo (PC) activity found during surveys for breeding sites. For visuals, see Figure 4.

Evidence	*Likelihood of Palm Cockatoo use*
Worn edges of hollow (from walking)	Possible (can also be Sulphur-crested Cockatoo or Red-tailed Black-Cockatoo)
Chewed edge of hollow	Moderate (can also be Red-tailed Black-Cockatoo: D. Teixeira pers. comm.)
Branches near entrance of hollow smoothly snipped at angle of 45º	High
Smoothly snipped branches (45º angle) on ground	High
Smoothly snipped whole sticks (45º angle) on ground	Extremely high
Splintered sticks on ground (cleanly snipped at 45º angle at ends)	Extremely high
Snipped sticks lodged on or near entrance of hollow	Extremely high

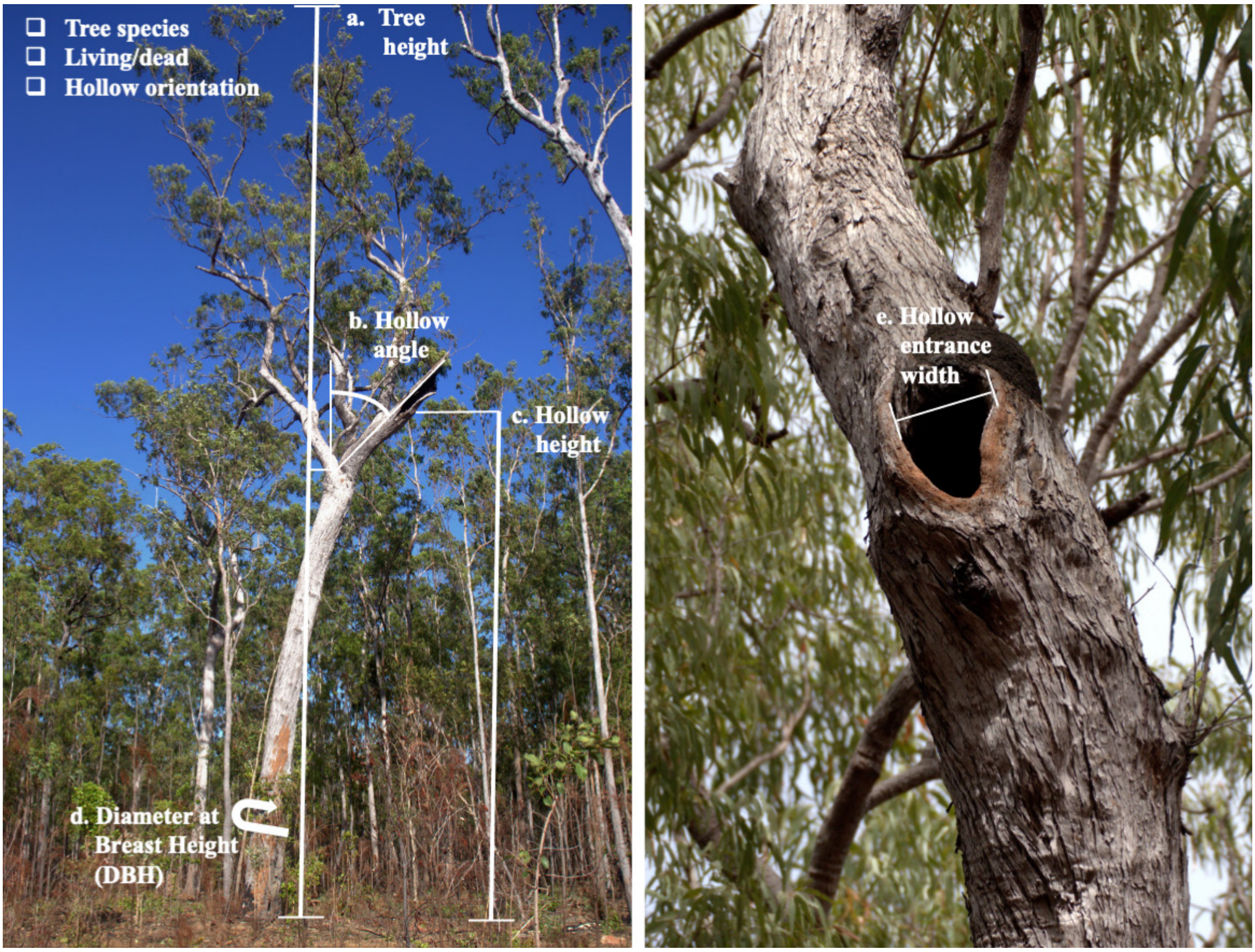

Figure 2. Parameters used to quantitatively and qualitatively describe tree hollows. Adapted from Murphy *et al.* (2003) for ease of use.

5. Walk transect lines during daylight. A recommended traverse speed is completing 2.0–3.5 km of transect every hour but this depends on the experience of the observers, the density of vegetation, and the number of hollows encountered. Navigators should follow the transect lines as close as possible (ideally within 10 m) to maintain parallel traverses, a maximum of 100 m apart.

6. Identify and record all potential, used, suspected nesting, and confirmed nesting hollows (Table 2).

   (a) When a hollow is identified, deviation from the track is necessary to view the hollow from different angles and to measure it (Figure 2), and to observe and note any nesting material under hollows or (if hollow tree is dead) adjacent trees. Use binoculars to observe

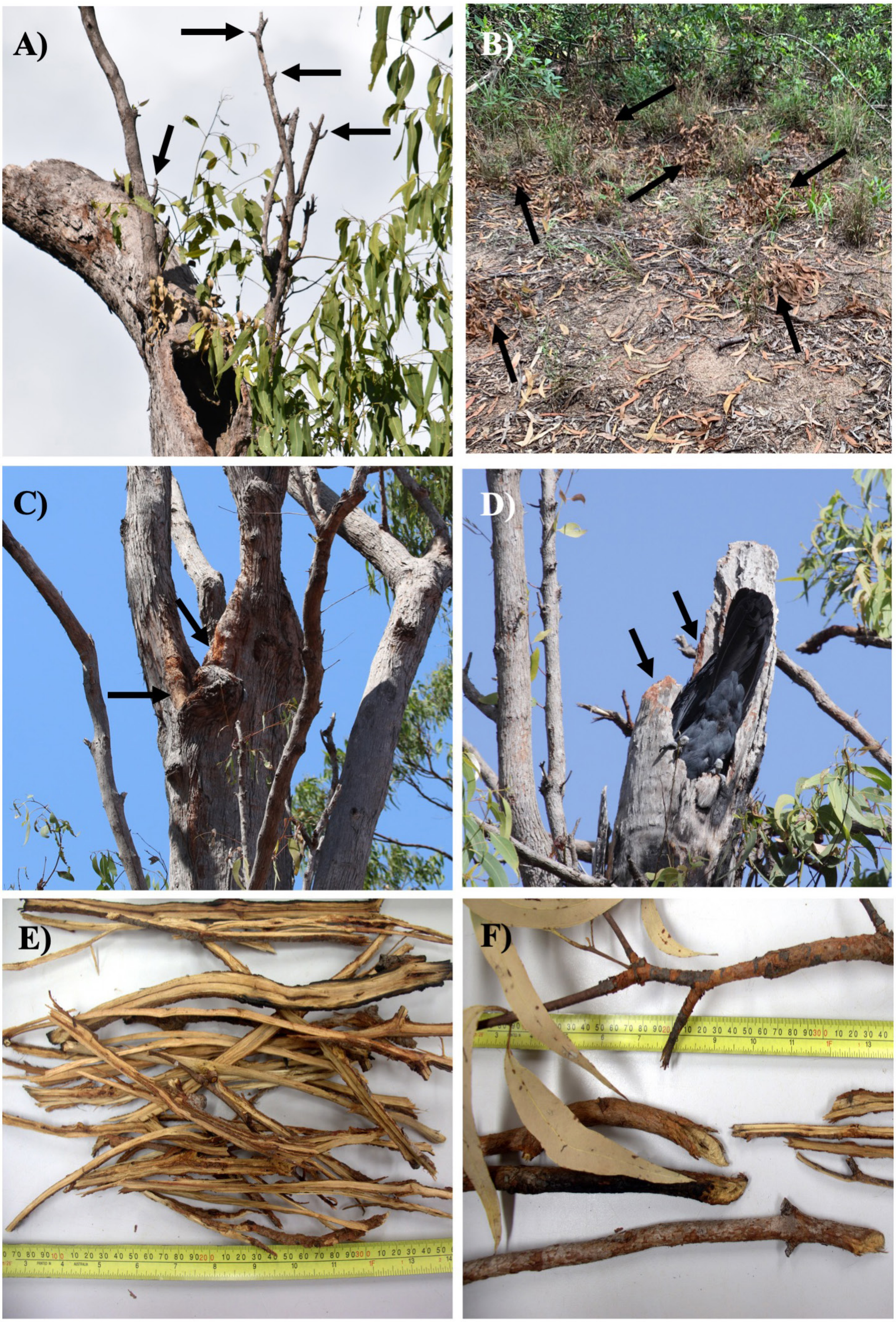

Figure 3. Signs of Palm Cockatoo breeding activity at hollows Class 2, 3 and 4 (see Table 2). (A) Snipped branches at hollow or adjacent trees (black arrows), (B) Snipped branches on ground, near a hollow in an adjacent tree, (C) Wear marks at the edge of hollow (black arrows), (D) Bite marks at hollow (black arrows) where a Palm Cockatoo has been entering the hollow head-first, (E) Splintered nesting sticks found on ground under hollow, and (F) Variation of nesting materials found under hollows (including potential drumming sticks). We caution that some nesting hollows have none of these signs. All images from sites in western Cape York Peninsula except D, from Lockhart River. Photos: A–C, E–F: Celina V. Cacho, (D): M. Willis & Christina N. Zdenek

detailed aspects of the entrance to the hollow, such as wear, snipped branches near the hollow (Figure 3), and/or termite mud nesting material filling the 'hollow' (which can result in overestimation of hollow presence in the landscape: Penton *et al.* 2020)).

(b) Any additional evidence of Palm Cockatoo activity or bird presence is noted as supporting information for subsequent surveys. If a Palm Cockatoo is detected, a stationary scan-and-listen session should be undertaken for 15 minutes to observe behaviour that could aid in classifying hollows.

(c) All measurements of hollows are recorded or estimated with paired-team consensus to help standardise measurements. Descriptions of methods for measuring these parameters can be found in Figure 2 and Appendix 1. Calibrating one's sense of distance in the field using a tree with precisely known parameters is recommended before beginning surveys.

7. For hollows deemed worthwhile to investigate further (e.g. suspected nesting hollows), use L-shaped brackets, screws, and a drill to install camera traps (i.e. automatically triggered cameras) at breast height on nearby trees with a view to the hollow of interest. Ensure settings (details below) are correct and the trap is on.
8. Any snipped branches/sticks (Figure 3B) found on the ground are either collected for data or piled up no closer than 10 m from the base of the hollow. The clearing of snipped branches and sticks from below the hollow assists the gauging of fresh activity in subsequent surveys. It also prevents accumulation of fuel load which could increase fire intensity and destroy the tree.
9. When required, replace batteries and memory cards of camera traps. We found that batteries required replacement every 3 weeks when cameras were set to time-lapse every minute between 0600 and 2000 h.
10. Review all camera-trap images and add data to a spreadsheet (if required). Decide what class a hollow is, based on Tables 1–2. Map locations of hollows for conservation and fire management.

Depending on funds, permits and goals of the survey, different thresholds for additional camera-trap installation to monitor hollows may be used. We used Reconyx Hyperfire infrared cameras set to 1-minute time-lapse. If Palm Cockatoos are observed emerging from a nesting hollow in the middle of the day (1000–1500 h), this indicates an active nesting hollow. If this is observed in person (not via camera-trap images), the survey team should leave the area and establish an exclusion zone around the nesting hollow (a minimum 200 m exclusion buffer is nominally used within our study area). Exclusion zones should only be entered—and done so as quickly and quietly as possible—for essential reasons such as installation, maintenance and retrieval of camera traps.

Signs to identify Palm Cockatoo hollows

The following methods have been utilised to identify potential and actual Palm Cockatoo breeding hollows in the field, including both nesting and display hollows. Pairs of Palm Cockatoos exhibit a unique behaviour during courtship that includes depositing twigs, branches and snipped sticks to create a nest platform (Murphy *et al.* 2003). Branches found on the ground, with an angle of 45º on their snipped portions, are characteristic of Palm Cockatoos snipping branches using their large beaks (Figure 3B; video at https://www.youtube.com/watch?v=N2twv-Ur294) and distinguish this species from other sympatric large parrots (e.g. Red-tailed Black-Cockatoo *Calyptorhynchus banskii* and Sulphur-crested Cockatoo *Cacatua galerita*). Such signs of display and nesting activity seen on the ground at the base of hollow-bearing trees can greatly aid in identifying active nesting or display hollows at any time of day. However, we strongly caution that some nests show no sign of activity, so hollows without these signs cannot be excluded as potential nest hollows. 'Messy' chewed ends of small branches are likely activity of other parrots. Likewise, Sulphur-crested Cockatoos can wear the lower edges of hollows by their claws via landing and walking, but they do not grind their beaks and break off chunks of bark along the edge of a hollow like Palm Cockatoos do (CNZ pers. obs.).

During the building of a Palm Cockatoo's nest platform, snipped sticks are split into strips (Figure 4) to drop into the hollow. The remnants of this activity (snipped branches and split sticks) are generally located on the ground (Figure 3E) around the vicinity of the hollow. Hollows in dead trees (i.e. stags) may have snipped branches under adjacent trees. The snipped branches usually have a maximum diameter of 20 mm, whereas the splintered sticks range from a stick split in half to long, thin fibres of wood/stick left on the ground (Figure 3). A summary of evidence of Palm Cockatoos used in the surveys can be found in Table 1.

Characteristics that *exclude* hollows for nest use by Palm Cockatoos, and therefore reduce observer effort and data management, include hollows that: (1) do not have an entrance that allows birds to land on the top/vertical edge or rim (Forshaw 1964); (2) have an entrance diameter <20 cm; (3) are at least partially filled with termite-mound material (Penton *et al.* 2020); or (4) are in trees with substantial fire damage, large holes and/or fissures within the trunk. A collection of confirmed nesting hollows with active Palm Cockatoo nests inside is provided for a visual reference (Figure 5).

Classification of hollows

We classified hollows as potential, used, suspected nesting and confirmed nesting hollows (Table 2). This classification enables the ranking of hollows for conservation purposes and the steering of future survey decisions, such as which hollows are monitored via camera traps.

An important caveat to classifying hollows according to Table 2 is that subsequent surveys may provide additional information that requires reclassifying the hollow. For example, the classification of suspected nesting hollow is intended as an interim classification until further investigation either elevates the status to nesting hollow or downgrades it to used hollow. Furthermore, although bushfires can destroy evidence of past Palm Cockatoo activity at hollows, they may also provide a timeline to

Figure 4. Views inside four Palm Cockatoo hollows. (A) Display hollow with a pile of mostly unsplintered sticks, (B) nest hollow with an abandoned Palm Cockatoo egg (later confirmed as infertile) on a flat nest platform, (C) adult Palm Cockatoo incubating an egg on a finely splintered nest platform, and (D) a young chick inside the nest hollow. Photos: A: Celina V. Cacho, B: C. Pumpa & Christina N. Zdenek, C: S. Adamczyk, and D: E. Thorpe

Table 2. Classification of tree hollows located during surveys to identify breeding sites of Palm Cockatoo (PC) on western Cape York Peninsula from 2015 to present.

Class	*Name*	*Description*
1	Potential hollow (possibly a PC hollow)	Suitable hollow, regarding: Size (diameter of entrance >20 cm), Position (bird can land at hollow), Angle (0–45º), and Height (>4 m above ground). No evidence to suggest it would NOT be suitable (i.e. no major fissures, no significant damage to walls of hollow, no substantial fire damage). No evidence of use (current or old).
2	Used hollow (has been used by PCs)	Use by PCs evident (Table 1): Any evidence of snipped sticks/branches at base of hollow or (if hollow tree lacks foliage) under adjacent trees. PCs observed in area (not necessarily for nesting but possibly for display as an essential component of breeding).
3	Suspected nesting hollow (confirmed use and suspected of being a nesting hollow but more evidence required)	Confirmed to be a used hollow (see above) with additional evidence that it may be a nesting hollow: Evidence of *splintered* nesting sticks at base of hollow, Evidence of excessive use relative to surrounding used hollows, Recent snipped sticks (i.e. with green foliage) at base of hollow, PCs observed at and/or near hollow, PC(s) reluctant to leave area, despite disturbance by survey team's presence.
4	Confirmed nesting hollow (is/has been used as a nest by PCs)	Confirmed to have been used for nesting PCs at some stage. Evidence includes: Fledgling seen in hollow or in tree of hollow, or Egg/chick observed in hollow, or adult observed in/on hollow in middle of day (1000–1500 h), or adults regularly observed entering and leaving a hollow in a nest-exchange manner.

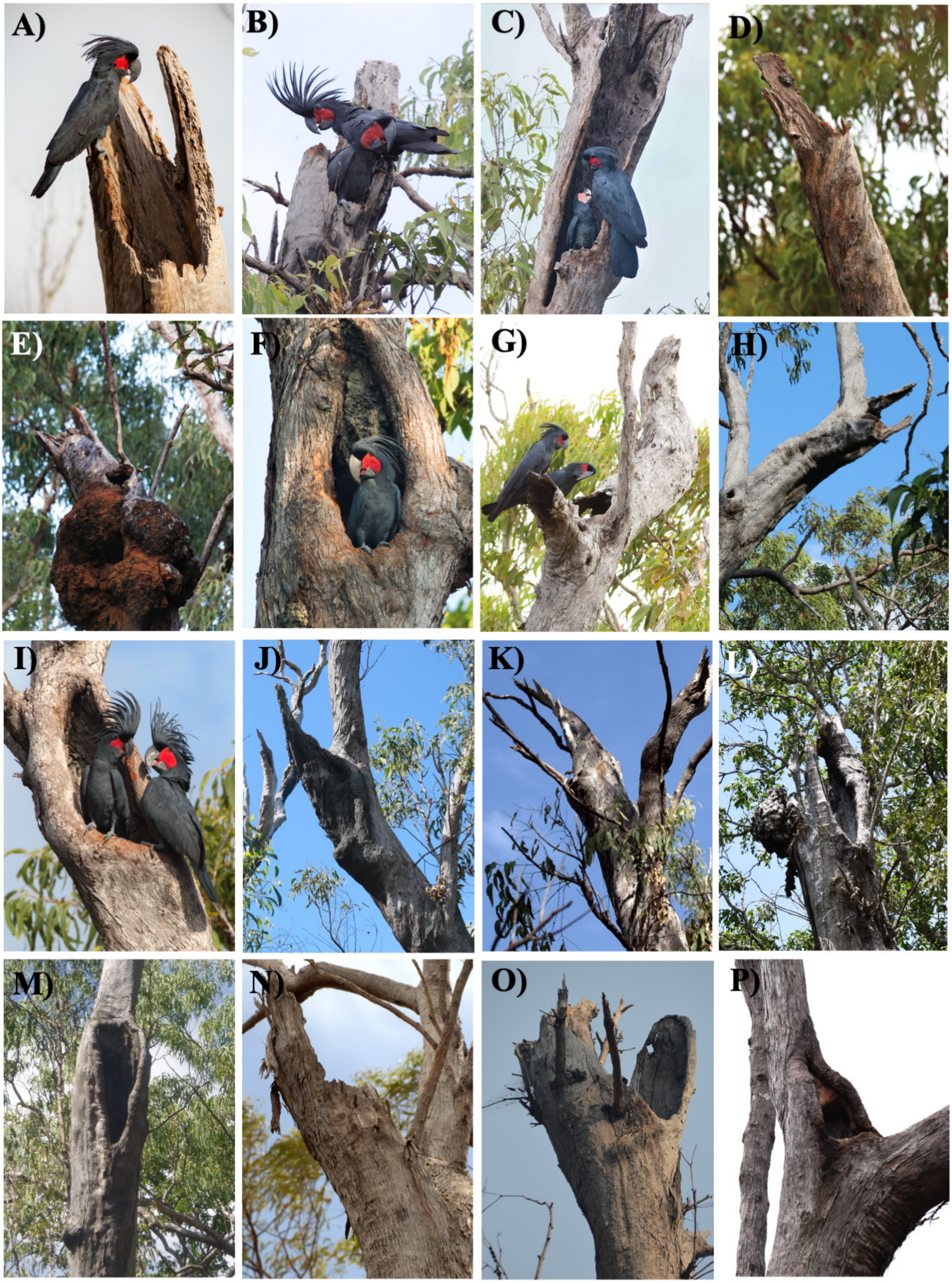

Figure 5. Sixteen confirmed nesting hollows of Palm Cockatoos on Cape York Peninsula: A–J at Iron Range (eastern coast), K–P near Weipa (western coast). Photos: A, D–J: Christina N. Zdenek, B: M. Willis, C: J. Griffith, all others: Ecotone Flora and Fauna Consultants staff

Table 3. Number and categories of hollows found during surveys for hollows used by Palm Cockatoos on western Cape York Peninsula (2015–2020).

Category	*Hollow class*	*No. identified (total)*	*Percentage of total*
Potential hollow	1	5003	91.2
Used hollow	2	438	8.0
Suspected nesting hollow	3	18	0.3
Confirmed nesting hollow	4	27	0.5
Total		5486	100.0

indicate fresh nest-building activities post-fire if the burn date is known.

Justification for recommended method

The survey methodology recommended here has been by used by field ecologists working on western Cape York Peninsula during field seasons from October 2015 to November 2020. Approximately 78,050 ha of land were covered, with 7805 km of potential habitat traversed by field teams, and an additional 2205 km traversed for a second time during subsequent surveys. The number, category, and class of hollows found are shown in Table 3.

On average, these totals equate to one hollow confirmed to be used by Palm Cockatoos (Classes 2, 3 and 4) being encountered every 16.16 km traversed (one used hollow every 161.6 ha), and one confirmed nest hollow (Class 4) being identified every 289 km traversed (one confirmed nest hollow every 2890 ha of potential habitat traversed). This traverse methodology has also resulted in the identification of three nests of the Endangered Red Goshawk *Erythrotriorchis radiatus*, or on average one confirmed nest every 2350 km traversed (one confirmed nest every 26,000 ha of potential habitat traversed).

Methods

Study area

Cape York Peninsula is characterised by a tropical, seasonally monsoonal climate, with an average annual rainfall of 2039 mm, primarily falling during the wet season (December–April). Western Cape York Peninsula features tall savannah woodland to open forest (20–36 m high), dominated by tall stands of Darwin Stringybark on lateritic plateaus (Figure 6). This is dissected by narrow watercourses of riparian woodlands, localised patches of vine forest and paperbark sinkhole swamps (Taylor *et al.* 2008), which support foraging corridors for Palm Cockatoos. Palm Cockatoo hollows in this area are located primarily in savannah woodland, adjacent to vine thickets, spring-fed drainage zones and riparian feeding corridors.

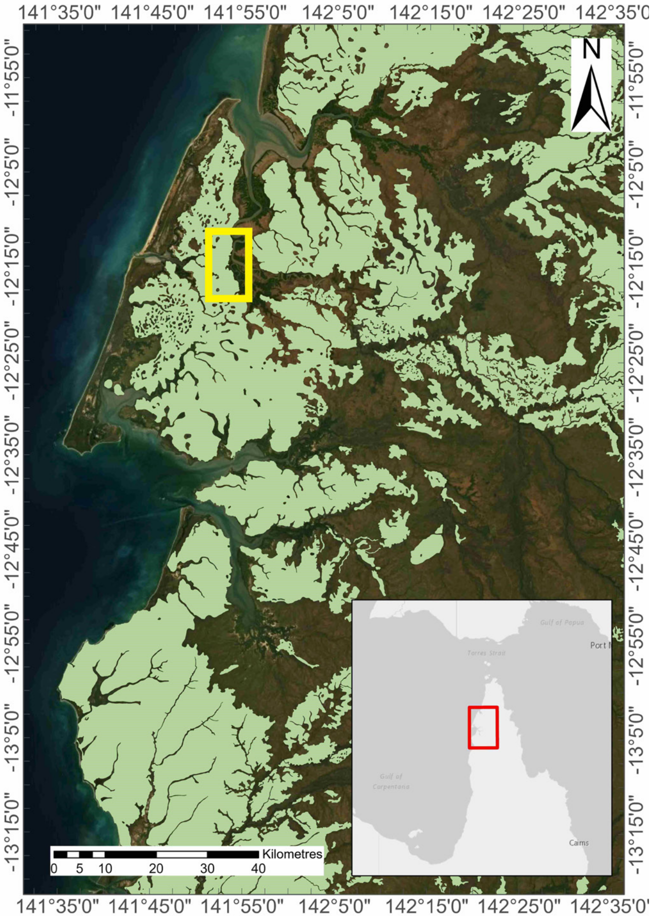

Figure 6. Study area of western Cape York Peninsula in northern Australia. The methodology was implemented between 2015 and 2020 in some areas of the lateritic bauxite plateau mapped light green and supporting Darwin Stringybark (Queensland Goverment 2019). The verification survey in 2021 was undertaken in the area marked with a yellow box.

Assessing and refining the methodology

The described methodology was applied in field surveys, tested on three pairs of observers in the same survey area, and refined. We tested one pair each in three observer treatment groups (experienced, intermediate and novice), with each group varying in level of experience in identifying and classifying Palm Cockatoo hollows. Group categories were established based on observed learning timelines of field assistants participating in this work since 2015. Experienced observers had at least 2 years of experience in the field identifying Palm Cockatoo hollows, intermediate observers had ≤5 months, and novices (with degrees in environmental sciences) had no previous experience on Cape York Peninsula or with Palm Cockatoos.

Four previously surveyed sites were traversed over 4 days by each of the three pairs. Each group was provided with identical transect tracks, start points and methodology (which was slightly refined after this initial verification exercise and is the reported method here). No further training was provided. Data from previous years could not be used as a comparative baseline because of the episodic creation and loss of hollows over time (Murphy & Legge 2007). Instead, we considered the experienced observer group to have the strongest assessment of actual Palm Cockatoo hollows in the landscape to compare with other treatments.

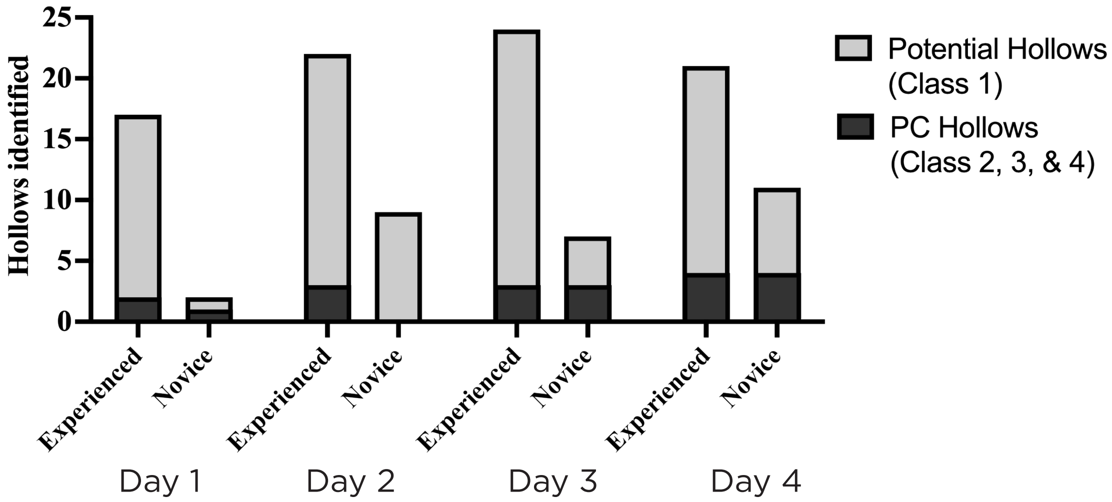

Figure 7. Comparison of numbers of hollows showing signs of use and potential hollows of Palm Cockatoos (PC) identified by experienced and by novice observers over a 4-day period. A simple linear regression (y = 0.1088x + 0.0793; not shown) of the proportion of all hollows identified by novice observers compared with experienced observers over time returned R^2= 0.91.

As experienced observers traversed a greater distance daily, we standardised comparisons by including only hollows that fell within the traverse area of the novice treatment (i.e. shortest distance).

Results

The experienced pair of observers traversed an average of 12.61 ± standard error 0.68 km/day, the intermediate pair 11.93 ± 0.57, and the novice pair 10.07 ± 0.89 km/day. In a 4-day period, experienced observers identified a total of 137 hollows, 12 of which showed evidence of use by Palm Cockatoos (Class 2, 3 and 4 hollows). Of these used hollows, the intermediate and novice groups found 91.6% and 75.0%, respectively. For total hollows (i.e. those found by experienced observers, n = 137), inclusive of potential hollows ('total hollows' was used as a proxy for current hollow presence), intermediate and novice groups found 47% and 33%, respectively. However, after having viewed the unrefined methodology before the test surveys, the novice group demonstrated a very quick learning curve, finding 15.7% of total hollows on Day 1, and 64.0% by Day 4 (Figure 7). Results from a simple linear regression (y = 0.1088x + 0.0793) of the proportion of all hollows identified by novice observers compared with experienced observers over time returned R^2 = 0.91. Compared with the experienced pair, the novice pair found one additional hollow on Day 4 by straying >50 m beyond the transect line to follow up Palm Cockatoo vocalisations; this was excluded from analysis as it was outside the survey bounds.

The identification of potential Palm Cockatoo hollows shows more variance between observers and appears to carry a higher degree of subjectivity over the classification and acceptance of potential hollows (Class 1), although this variance decreases as observers become more familiar with both the method and tropical working conditions. Our results indicate that novice observers who use this method find a considerable proportion (~75%) of hollows used by Palm Cockatoos, with a robust learning curve and a 51.0% increase in the number of hollows identified over a 4-day learning period. Additionally, the methodology presented here has been refined following this reliability test to include further supporting information and images to increase rates of identification of hollows.

Discussion

Here we illustrate the success of—and details for—a systematic survey method to identify nest hollows of the Palm Cockatoo, one of Australia's most iconic and endangered parrots. This proven method and its refinement have benefited from years of observing the behaviour of Palm Cockatoos, and enable ecologists to achieve greater success in surveying for Palm Cockatoo nesting hollows. Large hollow-bearing trees are crucial for Palm Cockatoo reproduction, yet their fully hollowed (and sometimes dead) nature makes them vulnerable to destructive hot fires, and the old age of these trees (probably >250 years: Woinarski & Westaway 2008) renders them effectively irreplaceable.

The unique nest-building behaviour of this species facilitates a reliable survey method that may not be suitable for other species. In general, parrots are notoriously difficult to survey for several reasons: they often cannot be caught and tagged (Zdenek 2012), they often occur in forests with closed canopies (Gilardi & Munn 1998), and many occur in tropical regions where monsoonal rain precludes surveys for 3–4 months each year (Forshaw 2011). Palm Cockatoos are no different in this regard: multiple attempts at catching individuals to mark them have failed, and their habitat experiences annual wet seasons. Furthermore, in surveying for their nest sites, previous methods for locating nesting hollows have relied on the presence of Palm Cockatoos at or near their hollows, severely limiting survey times to only early mornings and late afternoons during breeding years. This likely leads to false absences because of biennial breeding (every 2.2 years on average: Murphy *et al.* 2003), protracted breeding seasons, and quiet nesting in this species (Zdenek *et al.* 2015). Our method excludes the need for bird presence, which is possible because their unique nest-building behaviour leaves physical clues, enabling full-day surveys and a longer survey window in the year.

To our knowledge, no such systematic survey method as provided here has been published for parrots. Amongst large mammals that use large hollows are the non-vocal, nocturnal Endangered greater gliders *Petauroides* spp., but surveys for them typically involve spotlighting or using real-time thermography (handheld infrared cameras) (Vinson *et al.* 2020), with no signs available to aid surveyors to identify recent presence except flattened pea-sized faeces that may be detected by expensive (AU$40,000) conservation dogs. Similarly, surveys for large owls that nest in large hollows rely on detection of animal presence via spotlighting, vocalisations and call-playback (Wintle *et al.* 2005). Surveys for hollow-reliant species that require active animal presence severely limit survey effort and thus spread limited conservation funding thinly. Without the method presented here, Palm Cockatoo surveys would be similarly severely limited.

One common method gaining traction for efficiently surveying wildlife is camera traps (Burton *et al.* 2015). A comprehensive review of 266 camera-trap studies (Burton *et al.* 2015) revealed that most studies detect ground-dwelling species (primarily mammals), with only 11.9% of previous studies focusing on birds. For example, one study placed camera traps 46–65 cm from birds visiting a feeder/nest (Randler & Kalb 2018). Most observations of rare, flying bird species appear to be opportunistic (O'Brien & Kinnaird 2008). Although time-lapse cameras installed in trees to monitor natural (Honey *et al.* 2021) or chainsaw hollows (Griffiths *et al.* 2020) is not novel, the method of installing eye-level camera traps angled upward to detect occupancy of tree hollows is, to our knowledge, a new approach that reduces the cost of installation/maintenance immensely. Traditional motion-sensor detection settings are not suitable for this type of monitoring at distance because of canopy movement in a wide-angle frame. Instead, by using time-lapse (one photograph/minute) and analysing images manually, we could confirm/exclude use by Palm Cockatoos. When using the proposed time-lapse rate (one photograph/minute) for the whole breeding season, there is no chance of missing breeding events at any particular hollow because of the extensive nest building/maintenance, displaying and nest-exchanging (alternating incubating duties between the male and female) required for Palm Cockatoos to breed. Moreover, a more frequent time-lapse interval reduces battery life, requires more maintenance visits to each nesting hollow, and increases the potential to cause disturbance to breeding. Given the protracted breeding season of Palm Cockatoos, their biennial nesting, and their wary nature (causing nesting birds to quietly flush from their hollows upon approach), the use of camera traps is a key pillar in the identification and classification of hollows used by Palm Cockatoos in order to avoid false absences.

Palm Cockatoos may maintain and defend up to seven hollows during the breeding season (CNZ pers. obs. via photo-identification), but on average three to four hollows (Murphy *et al.* 2003), suggesting that display hollows may be used as a 'back-up' if the primary (nesting) hollow succumbs to predation, fire or wind. The very small proportion that we found of hollows used as nesting hollows (0.5%: Table 3) suggests that either (1) the population is small in comparison with the availability of hollows, or (2) Palm Cockatoos are extremely selective of their nesting hollows and that these resources are rare in the landscape. Genetic evidence obtained from four nests on the eastern coast of Cape York Peninsula suggested that the adults re-use the same nest between breeding attempts, even 3 years apart, but that nest ownership can also change (Murphy *et al.* 2003). We note that many suspected nesting hollows could not be regularly monitored and established as confirmed nesting hollows because of their remote location or inaccessibility.

Fire is a major feature of the Cape York Peninsula bioregion, with 40–70% of western Cape York Peninsula burnt annually (Felderhof & Gillieson 2006). Tree species there are strongly affected by synergistic hollow-forming processes of fire, storms, termites (Isoptera) and fungi (Perry *et al.* 1985; Murphy & Legge 2007; Woolley *et al.* 2018). Large hollows (>20 cm wide) in these trees take centuries to form (Woinarski & Westaway 2008), but intense fires burn many trees down to the ground each year. For example, hollows shown in Figures 4A–F burned down in hot (late dry-season) fires over a 6-year period. Tropical savannas make up >75% of the area burnt in Australia every year, despite making up only 20% of Australia's land area (Russell-Smith *et al.* 2007), making fire management a prominent feature for conservation in this habitat. Fire management is especially important for avian species (such as Palm Cockatoos) in a fragmented landscape or those with "a restricted distribution, limited reproductive potential, poor dispersal ability, and/or narrow habitat requirements" (Woinarski & Recher 1997, p. 183). In addition, old trees are particularly vulnerable to loss (Woinarski & Westaway 2008; Lindenmayer *et al.* 2014). Thus, consideration should be given to creating firebreaks of radius 3 m (using brush-cutters/whipper-snippers and blowers/rakes) around all used hollows, and particularly confirmed nesting hollows, because of the often overly frequent and intense bushfires in tropical Australia (Woinarski & Legge 2013). However, this manual effort is very labour-intensive, making appropriate fire management on a landscape scale more desirable across large regions over time. Fire management is clearly a critical aspect of Palm Cockatoo conservation, and the identification of nest hollows can help guide fire management plans and priorities.

In conclusion, decisions on land management to support Palm Cockatoo breeding areas require careful consideration of the life-history traits of this vulnerable species. Habitat connectivity between breeding places (including display hollows) and riparian feeding corridors ensures that adequate food is available during breeding, increasing the fitness of both adults and fledglings. In addition, riparian corridors and rainforest patches are used as cover by fledgling Palm Cockatoos up to 9 months or more after fledging (CNZ pers. obs.). Thus, we recommend the creation of a connected network of buffers around used hollows and suspected and confirmed nesting hollows with habitat corridors, connecting with riparian/rainforest edges wherever possible. Placing a protected buffer (safe from land clearing) around Palm Cockatoo hollows supports the integrity of the surrounding ecosystem and increases the resilience of hollows to edge effects (i.e. strong winds, fragmentation: Lindenmayer 2017). Furthermore, high-density breeding areas that support multiple breeding pairs should be considered for larger, more extensive protection and management because such areas may act as strongholds for a local population by enabling genetic connectivity and feeding corridors.

This systematic survey method aids ecologists and land managers to successfully identify nesting hollows of the Palm Cockatoo, one of Australia's most iconic and vulnerable parrots. In our experience, this method is critical to avoid false absences and to successfully map and safeguard breeding places against change in land use. Overall, the identification and protection of Palm Cockatoo hollows is paramount for the conservation of this endangered species, and the methodology provided here shares the knowledge to do so successfully.

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Appendix 1. Characteristics of trees and hollows in them that are used by Palm Cockatoos (PC) and methods to measure these (see also Figure 2).

Parameter	*Method of measurement*
Tree	
Species	Positively identify by trained observers.
Status	Determine if living or dead.
Height (m)	Total height, from ground to highest point in canopy. A digital measuring device (i.e. Nikon laser rangefinder or equivalent) is preferable to measuring 'by eye'.
Diameter at breast height (DBH, cm)	Use standard or DBH tape measure.
Hollow	
Orientation	Compass direction that entrance faces.
Angle (°)	Based on a centreline through middle of top metre of hollow. Estimate by standing orthogonal to direction that hollow is leaning, ensuring that tree is not leaning towards viewer. Estimate to nearest 5°, inclusive of 0° as the zenith.
Height above ground (m)	Measure from ground to base of opening of hollow.
Entrance width (cm)	Based on widest part of most likely entrance point of Palm Cockatoo into hollow. If opening cannot be seen, base estimate on diameter of tree near opening of hollow.