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PRACTICE AND TECHNICAL ARTICLE

Creating entrances to tree cavities attracts hollow-dependent fauna: proof of concept

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Redressing the paucity of tree hollows is essential for conservation of hollow-dependent fauna in many landscapes around the world. We describe a method of accelerating availability of natural hollows in regenerating landscapes by mechanically creating entrances in tree stems that have existing voids or internal decay but have not yet developed entrances. We trialed this method in woodland and forest of south-eastern Australia in 39 stems in the closely related tree genera *Eucalyptus* and *Angophora*. Exploratory drilling of 10-mm diameter holes was used to detect the presence of internal decay or voids. We then drilled 40-, 65-, or 90-mm diameter entrance holes, depending on the size of the potential cavity, 2.4–4.8 m above ground level. Camera traps showed that drilled entrances were investigated or used within hours of creation. A diverse suite of invertebrates, reptiles, mammals, and birds were recorded entering or leaving entrances, including threatened species. All 39 holes were used by animals with up to six vertebrate taxa using some entrances. Two bird species excavated material from within cavities, and three species of marsupial were recorded taking nesting material into the cavities. This trial provides evidence that adding entrances to currently inaccessible internal cavities in trees has potential to accelerate development of habitat for hollow-dependent fauna, particularly in regenerating vegetation.

Key words: habitat enhancement, hollow-dependent wildlife, landscape restoration, mechanically created habitat, tree hollow, woodland restoration

Implications for Practice

- Trees can be assessed for the size of internal decay and voids by small-diameter boring.
- Natural internal cavities without entrances can be made accessible to fauna by simple drilling procedures.
- Created entrances provide access to a potentially diverse array of pre-existing cavities in trees that would otherwise not provide shelter or breeding sites for hollow-dependent fauna.
- Animal activity at created entrances can be monitored by camera traps, but these should be installed immediately, since animals may start investigating cavities within hours. A wide range of animal species used the newly accessible cavities.
- This method can facilitate early colonization of regenerating and replanted forests and woodlands by hollow-dependent fauna.

Introduction

Worldwide, loss of hollow-bearing trees threatens the survival of many species dependent on hollows (also termed cavities) for breeding and shelter (Cockle et al. 2011). Active interventions with artificial hollows have been deemed necessary in many parts of the world to conserve hollow-dependent fauna (Carey & Sanderson 1981; Copeyon et al. 1991; Cowan et al. 2021).

Planting trees is a long-term solution to the lack of hollows, but has long lag times to hollow formation (Rayner et al. 2014; Taylor et al. 2014). Natural hollow formation may be accelerated by reducing tree densities to speed growth, or inoculation with wood-decaying fungi, but may still have a lag of decades to hollow availability (e.g. Horner et al. 2010; Wainhouse & Boddy 2022). Such time frames greatly increase the likelihood of extinctions of hollow-dependent fauna (Manning et al. 2013).

A shorter-term solution is attaching nest boxes or salvaged hollow trunks or branches (log hollows) to trees or poles (Goldingay & Stevens 2009). This potentially caters for the requirements of a wide range of species (Goldingay & Stevens 2009), but mounting or structural failure mean they may last for less than a decade (Lindenmayer et al. 2009).

An alternative is creating hollows within individual trees by accelerating development through damaging or killing parts of

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the tree, or by direct mechanical creation (Carey & Gill 1983). Carey and Sanderson (1981) trialed routing holes in trunks to accelerate cavity formation. Despite 80% of cavities being used by arboreal mammals, they concluded the technique needed refinements due to an increased risk of tree collapse and some cavities filling with water. Around the same time, use of chainsaws to carve cavities directly into trunks or branches was tried (Gano & Mosher 1983). A plate of wood was removed, an internal cavity carved, and the plate reattached with an entrance hole drilled into it, but there was a 37% failure rate of the trees in the first year (Carey & Gill 1983). There seems to have been little attention given to this method until relatively recently with carved hollows now being trialed for a range of fauna species in Australia (e.g. Kenyon & Kenyon 2010; Rueegger 2017). Although successful in providing shelter and breeding sites, both nest boxes and carved hollows have demonstrable problems as substitutes for natural hollows.

Nest boxes require ongoing maintenance (Lindenmayer et al. 2009) and often fail to replicate the microclimatic conditions of natural hollows (Maziarz et al. 2017). Many nest boxes are never used, are only used by pest species (Lindenmayer et al. 2009), cater disproportionately for common species, or are only effective in the presence of larger trees (Le Roux et al. 2016). Carved hollows have advantages over nest boxes with respect to microclimate (Griffiths et al. 2018), but for safety reasons require an arborist to create them (Gano & Mosher 1983; Rueegger 2017). In either case, artificial nest boxes and carved hollows are not a complete solution to lack of hollows over broader landscapes due to the associated costs. Carved hollows also risk compromising the structural integrity of the tree due to the amount of trunk margin cut through and the size of the void created; the speed of creation means that the tree has not produced compensatory growth to strengthen its stem as a void develops (Carey & Sanderson 1981).

Copeyon (1990) devised another approach, drilling a large hole into tree heartwood to create a cavity for use by woodpeckers (Copeyon et al. 1991). Taylor and Hooper (1991) improved the efficiency of this technique, but the process still required very precise drilling to prevent the created cavity flooding with pine resin, with fatal consequences for the birds. Despite these developments, finding additional means of accelerating hollow creation seems essential to redress the impact of lack of tree hollows.

Many Australian landscapes are devoid of hollow trees due to removal by humans (Manning et al. 2013). For the dominant hollow-bearing tree genera, *Eucalyptus* and the closely related *Angophora* and *Corymbia* (Myrtaceae), evidence from a range of sources indicates many trees contain natural internal cavities without external access. For the widespread temperate woodland *Eucalyptus populnea*, Harrington (1979) found that all stems greater than 19 cm diameter at 30 cm aboveground were hollow. Yet, *E. populnea* trees have a mean increase in diameter at breast height (dbh) of 0.24 cm per year (Taylor et al. 2014), and need to be 30–40 cm dbh for a 50% probability of having external openings greater than 1 cm (Rayner et al. 2014). Similar discrepancies between the presence of internal decay and external entrances exist for the even more widespread *E. camaldulensis* (Ellis 2018) and are reported as common in other tree species (West 2009).

Based on this evidence, we hypothesized: (1) Where we could identify trees with internal decay or voids, we could create entrances into existing natural cavities that may not otherwise be exposed for decades; (2) In stems with internal decay, providing an opening would allow animals (invertebrates, or vertebrates such as parrots), or gravitational forces to empty some of the decayed material to create a useable void; and (3) A range of species would use created entrances to access these natural voids for shelter and breeding.

Methods

Study Areas

We chose two study areas in south-eastern Australia. The first was in highly fragmented, remnant and regenerating temperate woodlands in the ex-farmland of Warrumbungle National Park (hereafter the park) (−31.30°S, 149.01°E). Here, past land use has resulted in a paucity of hollow-bearing trees and many stems are small (<50 cm dbh) and relatively young, either because they were planted since the park gazettal 50 years ago, or are basal resprouts of trees damaged in fires. After fire burned almost 90% of the park in 2013, many damaged trees were felled (to protect visitors), revealing heartwood decay or voids in some small stems. The second study area was on the New South Wales south coast (−36.54°S, 150.03°E) in previously logged mesic forest where landholders reported that regenerating tree stems of 40–65 cm dbh frequently contained decaying cores.

Entrance Creation

We selected trees in areas away from roads and walking tracks, and from the ground we visually inspected the trees for existing hollow entrances. In trees lacking entrances, we tested for internal decay/voids, by drilling inspection holes of 10-mm diameter and up to 200 mm depth into trunks. Resistance to drilling was used to assess whether a void or decay had been encountered. Where a void/decay was detected, the tree was ascended using a ladder and the internal void tracked upwards by drilling further 10-mm inspection holes until a suitable point for creating an entrance was found (void/decay through <200 mm of wood, > 40 mm diameter, accessible via ladder; additional details in Figs. S1 & S2).

Three entrance diameters (40, 65 and 90 mm) were trialed to facilitate access by vertebrates with a range of body sizes. For each stem, we chose an entrance size no greater than the estimated diameter of the internal cavity. To define the entrance size, a hole saw was used to cut the first few centimeters into the stem and the timber was removed using a hammer and chisel. An auger, twist, or spade bit was then used to make multiple holes to extend the entrance through to the void with the remains of the timber removed with a chisel (Fig. S1). The initial trial created entrances in November 2017 in three stems on which to test our monitoring techniques. Once the installation and monitoring techniques were determined to be feasible, the trial was extended. Between April 2018 and September 2019, we added entrances into an additional 21 stems in the park, and 15 stems on the south coast.

Entrance holes were made through 60–200 mm of wood, at 2.4–4.8 m above ground level, and accessed voids or decay of 40–240 mm diameter (Fig. S2). Stem dbh ranged from 28 to 80 cm. Holes were created in: *Eucalyptus blakelyi* ($n = 6$ stems), *E. albens* ($n = 8$), and *E. melliodora* ($n = 10$) in the park; and *E. tereticornis* ($n = 1$), *E. sieberi* ($n = 4$), *E. longifolia* ($n = 2$), *E. muelleriana* ($n = 6$), and *Angophora floribunda* ($n = 2$) on the south coast. In the park, four of the entrances were in trees planted in the 1980s to revegetate cleared areas, other drilled entrances in the park and the south coast were in naturally regenerated trees.

Monitoring

A camera trap (initially PixController, replaced by Reconyx Hyperfire 2 IR in 2018) was mounted on a bracket above each entrance, with the camera suspended 75 cm from the stem facing the entrance (Fig. 1). This arrangement prevented animals using the bracket for easy access to the entrance. Cameras were triggered by inbuilt motion sensors aimed near the entrance and continued taking still images until movement ceased. Images were downloaded regularly until summer 2019–2020 when bushfires forced removal of equipment from the south coast and the subsequent COVID-19 travel restrictions limited further visits.

Images were viewed to determine if an animal had triggered the camera and the animal's behavior recorded. Photographed events were classified as: "incidental" for no apparent interaction with the entrance and were not further considered; "inspection" where the animal approached to the edge of the entrance and inserted its head into the hole; or "use" where the animal was recorded entering or exiting the entrance or was active inside the hole. Frequently, individuals were recorded entering but not exiting, or occasionally vice versa. Due to the speed of animals compared to the camera frame rate and the nature of the sensor pattern, some events may have resulted in animals entering holes but the actual moment of entry not being recorded.

Figure 1. Camera mounted on a bracket attached above a drilled hole giving access to internal void allowing the camera to photograph inside the entrance and adjacent area of the trunk. String to the side is attached to a temperature logger.

Temperature loggers (Thermochron iButtons, Maxim Integrated Products) with a 0.5°C resolution were used to record temperature every 30 minutes in 10 cavities for 2 weeks in summer 2020 on the south coast. Loggers were anchored outside entrances and suspended into the cavity on a string (Fig. 1). Ambient temperature was recorded in a Stevenson's screen nearby. Attempts to record temperatures in other cavities failed due to animals pushing the loggers out.

Results

Photographic Records

During the feasibility trial, two of the three cameras worked and took photos between November and December 2017. One camera took four photographs revealing displaced debris but no animal. The other took nine nocturnal photographs; eight showed feathertail gliders (*Acrobates* sp.) entering the hole (Fig. S3), though none showed animals leaving. Based on the characteristics visible in photographs, there were at least two individuals and they were most likely to be *Acrobates frontalis* (van Dyck et al. 2013). Reliable cameras became available in April 2018 and these operated from April 2018 to December 2020. At no time did a memory card exceed capacity, but there were occasional interruptions when cameras were knocked out of alignment by strong winds or falling branches.

Events photographed by the 39 cameras ranged from single frames containing an animal through to series of up to 157 consecutive images showing complex behaviors. Animals were recorded entering cavities within 5 hours of entrance creation and activity was photographed at two-thirds of the entrances within the first week after creation. So far, 25 vertebrate taxa have been recorded inspecting or using the created entrances, and also invertebrates such as spiders, centipedes and insects (Table 1). All created entrances were visited by invertebrates and vertebrates, with up to six vertebrate taxa using some entrances (mean 2.6 ± 1.6, median 2). The most widely recorded species were feathertail gliders in the park, and *Antechinus* spp. on the south coast.

The range of behaviors detected was extensive. Large lace monitors (*Varanus varius*) inspected cavities as if hunting, but entrance dimensions meant that only their heads and part of their bodies fitted in. Smaller reptiles including juvenile lace monitors entered and some remained in cavities overnight (Fig. S4). We recorded a rare example of a normally terrestrial blind snake (*Anilios* sp.) inspecting an entrance, apparently following an ant trail. Two species of cavity-nesting kingfishers, the sacred kingfisher (*Todiramphus sanctus*) and the kookaburra (*Dacelo novaeguineae*) (Table 1), were recorded excavating decayed core from two of the trees to enlarge the cavities (Fig. S5). Insectivorous birds inspected or entered some cavities, apparently foraging, with additional species foraging on invertebrates at entrances. Two species of marsupial gliding possums (Fig. S6) and an antechinus took nesting material into cavities, and an antechinus was photographed pushing juveniles back into a hollow (Fig. S7). Brushtail possums (*Trichosurus vulpecula*) were too large to enter but repeatedly and unsuccessfully tried to enlarge some 90-mm entrances.

Table 1. Number of entrances used by taxa that inspected, entered, or exited drilled entrances in the two study areas (WNP = Warrumbungle National Park; SC = south coast of NSW), and the size of holes used (S = 40, M = 65, L = 90 mm).

Animal	*Scientific Name*	*WNP*	*SC*	*Hole Size*
Invertebrates		24	15	S,M,L
Robust Velvet Gecko	*Nebulifera robusta*	1		M
Snake-eyed Skink	*Cryptoblepharus* sp.	4		S,M,L
Bar-sided Skink	*Concinnia tenuis*	1	1	M
Tree Skink	*Egernia striolata*	4		L
Lace Monitor	*Varanus varius*	1	5	S,L
Pale-headed Snake	*Hoplocephalus bitorquatus*	1		S
Blind Snake	*Anilios* sp.	1		L
Kookaburra	*Dacelo novaeguineae*	1	1	L
Sacred Kingfisher	*Todiramphus sanctus*	1		M
Rainbow Lorikeet	*Trichoglossus moluccanus*		1	L
Crimson Rosella	*Platycercus elegans*		2	L
Eastern Rosella	*Platycercus eximius*		1	L
Spotted Pardalote	*Pardalotus punctatus*		3	M,L
Striated Pardalote	*Pardalotus striatus*	1		M
White-throated Treecreeper	*Cormobates leucophaea*	8	7	S,M,L
Antechinus	*Antechinus* sp.	4	12	S,M,L
Brushtail Possum	*Trichosurus vulpecula*	1	2	L
Ringtail Possum	*Pseudocheirus peregrinus*		2	L
Feathertail Glider	*Acrobates* sp.	20	8	S,M,L
Sugar Glider	*Petaurus breviceps*	3	2	M,L
Squirrel Glider	*Petaurus norfolcensis*	4	2	S,M,L
House Mouse	*Mus domesticus*	4		S,M
Black Rat	*Rattus rattus*	7	1	S,M,L
Long-eared Bat	*Nyctophilus* sp.	3		S,M
Insectivorous Bat	Chiroptera	2		M,L

Species interactions were recorded at some entrances. Feathertail gliders repeatedly started to enter a cavity occupied by a sparassid spider but retreated each time the spider moved toward the entrance. On another tree, a feathertail glider approaching a hole retreated as a robust velvet gecko (*Nebulifera robusta*) emerged, but the glider entered the hole once the gecko moved away.

Tree and Entrance Status

Between October 2017 and September 2019, we drilled inspection holes in approximately 125 tree stems in the park and 30 stems on the south coast which we suspected of containing decay or voids. Suitable cavities were found in approximately 20% of stems in the park and 50% of stems on the south coast. The 10-mm inspection holes which we did not enlarge (Fig. S1e) rapidly sealed over in live trees.

Vertical dimensions of accessed voids varied but these were not explored in detail. However, one of the 39 experimental stems was shattered by a tree falling on it, revealing that the void started near ground level and made a convoluted passage up past the drilled entrance (located at 3.2 m) for at least another meter. The remaining drilled stems were still standing in May 2021.

Until late 2019 woundwood growth was restricted to the perimeter of drilled entrance holes and all entrances remained open. In contrast, from 2020 to 2021 rapid growth started to occlude half of the holes (Fig. S8). This varied among trees and was not related to time of creation, with two holes created in September 2019 almost totally grown over by May 2021.

Cavity Temperatures

All 10 cavities were similar in temperature at any point in time and fluctuated by up to 4°C per day despite local ambient temperature fluctuating by up to 21°C (Fig. S9). Inside cavities the mean daily maximum was up to 14°C lower than maximum ambient, and mean daily minimum up to 10°C above minimum ambient.

Discussion

Our results provide evidence that: (1) drilled entrance holes are a viable way of providing access to existing internal tree cavities that have not yet developed external entrances; (2) a wide range of fauna will rapidly make use of such access; and (3) fauna are capable of modifying the cavities through excavation of debris or addition of nesting materials. Rapid use of drilled entrances (present study) and artificially excavated cavities (Rueegger 2017) by feathertail gliders clearly shows that activities associated with cutting or drilling into trees do not deter some species from immediate visitation.

Unlike many artificial cavities, the method we described here does not target particular animal species. Rather, it aims to increase availability in regenerating landscapes of an ecological characteristic typical of old-growth vegetation. The cavities accessed have formed naturally so are likely to be diverse in character, and this may explain the wide range of taxa we recorded using the entrances. The predominant use of our drilled entrances by mammals may reflect entrance positions (in trunks, <5 m above ground) or the types of cavities made accessible; entrances created through branches, higher, or accessing different types of cavities may attract a different suite of species. Conversely, mammals may be recorded more frequently because they use cavities throughout the year whereas birds use cavities mostly during their breeding season. Reptiles, being heterotherms, are less likely to be detected by camera as their temperature is indistinguishable from their background much of the time.

Since our cameras were designed for detecting large endothermic animals, there was a likely bias in the species photographed. Recording equipment with a faster reaction time than the cameras we used would be needed to better understand the interactions between animals and the created entrances. Additionally, activation of our cameras required thermally detectable animals to cross multiple points within the infrared sensor field, meaning not all visits would be recorded. A trigger mechanism located within the entrance may overcome this but may also deter animals from entering.

Our method creates an entrance into natural cavities within trees undergoing natural decay. Therefore, the cavity characteristics (e.g. shape, texture, thermal profile) and processes (e.g. growth, decay) should more-closely mimic those of natural hollows than do other artificially created hollows. Periodic closure of small natural or drilled entrances by tree growth is common (Carey & Sanderson 1981; Cockle et al. 2011), and variation in closure rate, as seen here, is typical of episodic growth related to water availability (Ellis et al. 2017). Our trees experienced drought conditions in 2017–2019, and above-average rainfall in 2020–2021. This indicates a need for periodic removal of woundwood from around the entrance to slow growth sufficiently to keep it open (which we are now trialing). This is also an issue with carved hollows (Best et al. 2022).

Like natural cavities with natural openings (Griffiths et al. 2018), the cavities accessed by our drilled entrances had relatively stable temperature. In stark contrast, wooden nest boxes can become far hotter than ambient air temperature, even in temperate environments, and fluctuate widely each day even when constructed to limit the impact of solar radiation (Maziarz et al. 2017; Griffiths et al. 2018; Ellis & Rhind 2021). Thus, denning or nesting in our artificially opened but otherwise natural cavities is likely to be less physiologically stressful than in nest boxes, and similar to modeling by Rowland et al. (2017) for natural hollows compared to nest boxes.

Several other advantages are apparent with the drilling technique trialed in our study. Because we use existing voids and decay within stems, the amount of timber removed by drilling is far less than in the Copeyon (1990) method but may give access to an extensive cavity system within the stem. The damage to tree stems caused by our drilling method is minimal compared to methods involving excavating an entire cavity using a series of drill holes and routing a void (e.g. Carey & Sanderson 1981), or by using a chainsaw (Gano & Mosher 1983; Rueegger 2017). The amount of stem circumference cut using our technique was only the diameter of the entrance hole, and the internal void/decay being tapped into had gradually developed prior to drilling. Thus, with our method the stem should have undergone additional resistant growth strengthening the stem, unlike the sudden imposition of structural alteration using cavity excavation methods (Carey & Sanderson 1981). Only long-term monitoring of trees treated by the various methods will resolve how important this difference is to the survival of the treated stems.

Our entrance-drilling method may also be more cost effective than chainsaw excavation, the Copeyon drilling method, or attaching constructed boxes, because far less wood working is involved. Our drilling method has the additional element of requiring stem testing to identify the presence of internal voids/decay, but both the exploratory stage and subsequent entrance addition can be done using a drill rather than a chainsaw. So, this type of cavity access can potentially be safely created without needing arborists. However, our method is reliant on the presence of stems with existing decay or voids, whereas the Copeyon's (1990) drilling method and chainsaw excavation can be applied to any stem large enough to cope with the amount of excavation required to create a cavity for the target species.

The slow process of identifying suitable trees is a disadvantage of our method, but the process was accelerated by use of local expertise about stem condition. There are also less invasive, but more expensive and cumbersome techniques that can be effective at detecting internal decay or voids in trees (see Soge et al. 2021). Future development of such techniques may make them feasible as landscape-scale conservation tools,

The efficiency of drilling access holes into existing cavities depends on the stem wall thickness. Our drill bits and hole saws allowed drilled entrances of up to 200 mm depth to reach the target area, unlike the excavation method where the face plate is only about 40 mm thick when the entrance hole is drilled (Kenyon & Kenyon 2010; Rueegger 2017). We found that drilling holes up to 32 mm diameter was achieved easily in a single action with an auger bit, and these were readily expanded to 40 mm using a hole saw. Larger-diameter entrances required several smaller holes to be drilled to remove some wood before using a larger hole saw to complete entrance creation. The most efficient equipment for drilling larger-diameter or deeper entrances has not yet been determined and will impact on the cost of extensive restoration projects.

The drilled entrance addition method described here is potentially another valuable management option in landscapes where hollows are in short supply and trees have a high probability of internal decay or voids but no access to wildlife. This method is worth pursuing because it: is relatively inexpensive and easily implemented, has low long-term maintenance requirements compared to other hollow augmentation methods, and uses natural cavities with the potentially complex structures that should cater for a diverse suite of hollow-using species. Temperate eucalypt woodlands of Australia are ideal for this technique because of their low and open structure and their drastic need for ecological restoration, but the method can also be applied in regenerating forests.

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Supporting Information

The following information may be found in the online version of this article:

Figure S1. Creation of a hollow entrance.
Figure S2. Diagram of a hypothetical section of tree trunk with an existing internal void.
Figure S3. Two individual feathertail gliders (*Acrobates* sp.) accessing the same tree hollow via a 65-mm drilled entrance.
Figure S4. Juvenile Lace Monitor (*Varanus varius*) exiting a 90-mm diameter drilled hole after overnighting inside the cavity.
Figure S5. Sacred kingfisher (*Todiramphus sanctus*).
Figure S6. Two species of gliding possum taking nesting material into cavities made accessible by drilled entrances.
Figure S7. An Antechinus (*Antechinus flavipes*) with a juvenile at a 65 mm drilled entrance.
Figure S8. Woundwood forming around a 90-mm drilled entrance in an *Angophora floribunda* 36 months after drilling.
Figure S9. Comparison of ambient temperature to temperatures inside 10 tree cavities made accessible by drilled entrances at the south coast study area.

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