A review of the management and monitoring of tree hollow resources for mammals and birds in the forests of New South Wales

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Introduction

One of the main consequences of native forest logging on fauna habitat is the loss of hollow-bearing trees. These trees have high ecological value because the hollows and cavities in the trees may be used as shelter and nesting sites by native mammals, birds, reptiles and frogs. The mammals and the birds that require tree hollows are particularly dependent because with few exceptions, they do not use alternative sites (Goldingay 2009, 2011). The mammals in particular are dependent because they use hollows year-round whereas most hollow-using birds only use hollows for breeding, and the birds have the mobility to enable them to search over a much greater area for hollows. That is, tree hollows are critical to the survival and reproduction of the hollow-using mammals, whereas they are most critical for breeding by hollow-using birds.

This report provides a literature review that was commissioned by the New South Wales (NSW) Natural Resources Commission (NRC). The information is needed to guide the Coastal Integrated Forestry Operations Approvals (Coastal IFOA) Monitoring Program, specifically the Key Habitat Features Monitoring Strategy.

The requirements for this review as requested by the NRC are as follows:

- "conduct a desktop study to compile and review peer reviewed literature relating to managing, monitoring or research on the use of hollow bearing trees in NSW forests, but also in other jurisdictions if relevant/transferable information,
- identify cost-effective approaches from sourced literature that could be used to monitor the use of hollows within the landscape by key species,
- highlight gaps in research that may be relevant for this Coastal IFOA monitoring strategy, e.g. for key species,
- assess the state of knowledge on hollow use in the published literature for key species including arboreal mammals (gliders), forest owls and microbats,
- review of the monitoring approaches used to determine hollow-use or hollow requirements for key species in the landscape,
- identify any gaps in knowledge on the use of hollow-bearing trees in a harvested landscape for the key species and if any further research is needed,
- recommend cost-effective monitoring approaches to consider the use of retained hollow-bearing trees in harvested areas, exclusions zones or clumps."

Tree hollow requirements of Australian mammals and birds

Gibbons and Lindenmayer (2002) provided a comprehensive review of the literature on the use of tree hollows by Australian wildlife. The literature specific to Australian birds and mammals was subsequently reviewed by Goldingay (2009, 2011) to provide a detailed account of the characteristics of nest and shelter trees, and to account for new studies that had been completed since 2002. It is not the intention here to review all of that information again, but to provide a summary of the key points that relate to: i) the size of the trees used, ii) the size of the entrances to hollows, and iii) some indication of the spacing of the trees used. Based on the species-specific information, I provide some recommendations relating to what should be considered if devising prescriptions for tree retention in areas subject to logging.

In relation to the number of trees required by different species the literature is inconclusive. Most birds use hollows only for breeding and therefore may only require one hollow per individual per year. For arboreal mammals it is more complex. Studies have documented the number of trees used by a number of individuals of different species. Many studies have been relatively short-term so their evaluation may be incomplete, and many have occurred where there is a high density of hollow-bearing trees so animals may simply use more trees because many are available. What has been revealed is that most studies suggest individuals use a subset of their dens at a high frequency. For example, Crane *et al.* (2010) found that squirrel gliders on the NSW south-west slopes used an average of 7 den trees each, but for 23 of 28 individuals, three den trees accounted for >60% of den use. Goldingay *et al.* (2015) found that six squirrel glider social groups persisted for 5–10 years in young forest (<30 years old) with access to 2–4 nest boxes per group. Martin (2006) found that mountain brushtail possums used an average of 7 den trees each, but for 26 of 28 individuals, three den trees accounted for >60% of den use. Kehl and Borsboom (1984) found that for 5 of 6 greater gliders, 2 den trees accounted for >50% of den use with the sixth glider using 4 den trees >50% of the time. Kavanagh and Wheeler (2004) found that all 7 greater gliders with >10 den records used 1–2 dens >50% of the time. Goldingay and Kavanagh (1993) found that five yellow-bellied glider groups used 1–4 den trees over periods of 1–5 years. Although based on a small number of studies it appears that about three hollow-bearing trees are required for these species to complete their annual cycle. The key point then is to provide hollows that meet the size requirements of the target species and with a spatial distribution so that individuals have access within their home range to at least 3 suitable trees. The key point that follows from this is that some attrition must be allowed for, so attrition rates of hollow-bearing trees need to be known.

Hollow-using non-flying arboreal mammals

This section provides a brief overview of what is known of the tree hollow requirements for a range of species that occur through the NSW coastal forests that are subject to timber harvesting. This does not include species such as the brown antechinus which is not viewed as tree hollow dependent to the extent that these other species are.

Greater glider – This species has been studied in detail by radio-tracking at two locations in NSW (Kavanagh and Wheeler 2004; Lindenmayer *et al.* 2004), one in Victoria (Lindenmayer *et al.* 1991a) and three locations in Queensland (Qld) (Kehl and Borsboom 1984; Comport *et al.* 1996; Smith *et al.* 2007). These studies provide sufficient insight to be able to generalise about greater glider requirements for tree hollows. Kehl and Borsboom (1984) suggested that greater gliders chose trees non-randomly with some species such as the broad-leaved white mahogany (*E. umbra*) and the forest red gum (*E. tereticornis*) (referred to as blue gum in Qld) used more than expected compared to other hollow-bearing trees. Smith *et al.* (2007) also found that forest red gum was used more than expected. Kavanagh and Wheeler (2004) found that the smooth-barked trees in their study area were used disproportionately more compared to their abundance. This may reflect a greater frequency of suitable hollows in those species but that was not assessed. Yellow-bellied gliders at the same location never used two of the rough-barked trees (*E. radiata, E. obliqua*) as dens (Goldingay and Kavanagh 1993), which may suggest those species were unreliable sources of suitable hollows at that location. However, *E. radiata* comprised 27% of greater glider den trees at Tumut (Lindenmayer *et al.* 2004).

Greater gliders choose den trees that are larger and taller than average (Kehl and Borsboom 1984; Lindenmayer *et al.* 1991a; Kavanagh and Wheeler 2004; Lindenmayer *et al.* 2004; Smith *et al.* 2007). Commonly the den trees are >100 cm in DBH. Greater glider home ranges usually average 1–3 ha in area (Kehl and Borsboom 1984; Kavanagh and Wheeler 2004; Lindenmayer *et al.* 2004), though at one location in south-east Qld four of seven individuals had home range estimates of >5 ha (Smith *et al.* 2007). The more typical small home range size has implications for the spacing of retained hollow-bearing trees. All studies have found that individuals use multiple dens trees with some, referred to as primary dens, receiving much greater use. To provide for greater glider denning requirements within logged areas will require the retention of many large hollow-bearing trees. The number of hollow-bearing trees actually required per glider is not known though it has been observed that gliders will have a small number of primary (i.e. most frequently used) dens ([1]Kehl and Borsboom 1984; Comport et al. 1996; [1]Kavanagh and Wheeler 2004; Lindenmayer *et al.* 2004). Only Lindenmayer *et al.* (1991b) provided any details of the types of hollows used, with hollow branches being highly preferred. Only Kehl and Borsboom (1984) documented the entrance size of hollows (Table 1). Anecdotally, the form of these hollows will be like those used by yellow-bellied gliders (see below) with large-volume hollows needed.

In summary, greater gliders prefer:

- large live DBH trees (≥100 cm)
- large volume hollows (i.e. large branches, opening into wide section of trunk)
- entrances <20 cm in diameter
- a relatively high density of these trees within retained clumps.

The availability of hollow-bearing trees in adjacent areas excluded from logging will complement any retained in the operational area.

Table 1. Den and tree hollow attributes used by focal species. Values are the range in mean values. (cm). Numbers in brackets show the number of studies contributing to those values. NA= not available; *includes nest box studies; [a]short-term areas only. Dens per ha is based on the number of primary dens per home range area.[1]Studies contributing to these values have this superscript in the text describing home ranges and den trees.

Species	DBH	Entrance diameter	% dead trees	Den spacing	Home range (ha)	[1]Dens per ha
Greater glider	58–128 (2)	18 (1)	7–16 (5)	20–150 (2)	1–3 (4)	1 (2)
Yellow-bellied glider	73–160 (3)	11 (1)	0–2 (4)	50–500 (3)	30–65 (3)	0.1 (3)
Squirrel glider	41–93 (5)	<5 (3)	8–54 (6)	20–300 (2)	5–15 (3)	0.4–0.6 (3)
Sugar glider	NA	<5 (3)*	NA	20–50 (3)*	4–5 (2)	0.4 (3)
Feathertail glider	66 (1)	<3 (4)*	NA	20–100 (4)	[a]0.2–2.1 (2)	NA
Brushtail possums	>70 (3)	10–20 (2)*	NA	20–100 (2)	2–6 (2)	1 (2)
Brush-tailed phascogale	>40 (3)	2.5–4.5 (3)*	5–35 (3)	10–400 (2)	15–120 (1)	0.1 (3)
Eastern pygmy-possum	57 (1)	<3 (4)*	20 (1)	10–200 (2)	3–4 (1)	0.3

Yellow-bellied glider – This species has been studied in detail (trapping and tracking) at two locations in NSW (Goldingay 1992, Goldingay and Kavanagh 1993), three in Victoria (Henry and Craig 1984; Craig 1985; Goldingay *et al.* 2018) and two in north Qld (Russell 1984; Goldingay and Quin 2004). These studies have provided sufficient detail on the use of den trees and tree hollows that it is probably sufficient to generalise for this species in areas subject to timber harvesting. Den trees are usually large living DBH trees (Table 1). Yellow-bellied gliders live in small groups (commonly a pair and offspring) that usually den together so they require a cavity sufficient in size for several individuals. Tree hollows can be in branches or in the main trunk of the tree. However, the den hollows used at Bombala in the study by Goldingay and Kavanagh (1993) were mostly in the trunk of trees (see Fig. 1). It's possible that such hollows may have been selected for the greater insulation provided relative to branch hollows due to the low temperatures commonly experienced at that location, or simply because they provided large cavities. A factor that was commonly observed at Bombala was that animals selected hollows with narrow entrances that they could just fit into. When animals select branch hollows the visible opening might be relatively large and possibly not reflective of the entrance into the main cavity. Den entrances may be high in a tree but it is likely that reflects availability and the types of hollows selected. In western Victoria den entrance height averaged 9 m but the lowest den was only 2.1 m above the ground (Goldingay *et al.* 2018a). Detailed studies estimating home range size and use have been conducted (Henry and Craig 1984; Craig 1985; [1]Goldingay 1992; [1]Goldingay and Kavanagh 1993; [1]Goldingay and Quin 2004) and show that glider groups use areas averaging 30–60 ha. The studies show that the den trees may be spaced quite widely through the home range. Den trees generally occur at a density of 0.05–0.1 per ha (Goldingay and Kavanagh 1993; Goldingay and Quin 2004).

In summary, yellow-bellied gliders prefer:

- large live dbh trees (≥100 cm)
- large volume hollows (i.e. large branches, openings into wide section of trunk)
- relatively narrow (~10 cm) entrances
- den trees that are widely scattered across their large home ranges.

Fig. 1. Tree hollows used by yellow-bellied gliders at Bombala, NSW, in the study by Goldingay and Kavanagh (1993).

Squirrel glider – This species has also been well studied in relation to its den requirements with radio-tracking studies conducted at two locations in NSW (Sharpe and Goldingay 2007; Crane *et al.* 2008, 2010), one in Victoria (Traill and Lill 1997) and three locations in Queensland (Rowston 1998; Beyer *et al.* 2008; Ball *et al.* 2011). In addition, there have been numerous studies conducted using nest boxes (Traill and Lill 1997; Durant *et al.* 2009; Ball *et al.* 2011; Goldingay 2015; Goldingay *et al.* 2015; Goldingay 2020) which provide additional insight about the use of shelter sites. Squirrel gliders prefer hollows and nest boxes with entrance sizes of <5 cm diameter (Table 1). Unlike the larger gliders they commonly use dead trees as dens. Beyer *et al.* (2008) demonstrated that this preference is more a reflection of which trees commonly have hollows rather than there being something preferred about a dead tree. This provides an important insight that no tree species are actually favoured, it is simply a matter of where the hollows are located. This notion is supported by the willingness with which squirrel gliders make use of nest boxes (Durant *et al.* 2009: Goldingay 2015; Goldingay *et al.* 2015). Crane *et al.* (2008) demonstrated that trees of greater size were favoured as dens and increasing distance to another tree reduced the chance of a tree being a den tree. The reason for the latter influence is unclear but it may relate to reducing the threat of predation.

Squirrel glider home range areas have been estimated at 5–15 ha ([1]Sharpe and Goldingay 2007; [1]Goldingay *et al.* 2010; [1]Crane et al 2014). The number of dens used by individual gliders averaged 7 trees in south-western NSW, though 2 would be considered primary (≥50% of records) ([1]Crane *et al.* 2010), but only 3 den trees in Brisbane and north-east NSW ([1]Sharpe and Goldingay 2007; [1]Goldingay *et al.* 2010). These studies suggest a spacing of den trees within a home range of 100–300 m. Nest box studies have shown that gliders may only need 2–3 nest sites and that a spacing of about 200 m may ensure use by different glider groups.

In summary, squirrel gliders prefer:

- live or dead hollow-bearing trees with larger DBH trees (≥50 cm)
- branch and trunk hollows equally
- hollow entrances of <5 cm diameter
- multiple potential den trees at approximately 0.5 per ha (Table 1).

Sugar glider – Surprisingly, few studies have described the den trees used by sugar gliders. Suckling (1984) provided few data on the 22 nest sites he examined. These sites were in dead and living trees, and were located in the branch or bole. One glider group used five trees within 300 m and another used three trees within a radius of 60 m. The deficiency in relation to studies of natural den sites is made up for by at least 15 studies that have documented use of nest boxes by sugar gliders (e.g. Beyer and Goldingay 2006; Durant *et al.* 2009; Goldingay *et al.* 2015). Sugar gliders favour nest boxes with entrance sizes of 3–5 cm diameter (Goldingay *et al.* 2020a). When provided with nest boxes which satisfy their den requirements sugar gliders can be highly abundant (Goldingay *et al.* 2015; Goldingay *et al.* 2018b). At Heathcote, Victoria, in one survey sugar glider groups occupied 32 of 40 nest box clusters ([1]Goldingay *et al.* 2020b). This study suggested that when their den requirements were satisfied other habitat variables had limited influence on occupancy. Nest boxes have been installed at 3–4 m above ground, highlighting that high dens are not a requirement for sugar gliders (Goldingay *et al.* 2015; Goldingay *et al.* 2018; Goldingay *et al.* 2020b).

The home range size of sugar gliders has been documented in a few studies. Only one has relied on radio-tracking. Suckling (1984) estimated seasonal home ranges of 0.2–1.0 ha based on trapping. [1]Quin (1995) estimated seasonal home ranges of 0.5–3.3 ha, whereas long-term home ranges (>3 seasons) averaged 3.8 ha based on trapping and using an 80% boundary derived from the harmonic mean method. In contrast, though in different habitat, [1]Quin *et al.* (1992) estimated home range areas of 5.4 ha using the minimum convex polygon and 3.5 using the 95% boundary from the harmonic mean method from animals that were radio-tracked.

In summary, sugar gliders prefer:

- live or dead hollow-bearing trees
- branch and trunk hollows equally
- hollow entrances of <5 cm diameter
- multiple potential den trees at approximately 0.5 per ha (Table 1).

Feathertail glider – The feathertail glider is another species for which there are scant data on its den trees. Ward (2004) radio-tracked five gliders to 15 den trees but was unable to locate where the gliders were sheltering. The mean DBH across different tree species was 44–79 cm. There have been several nest box studies which have provided some insights (Ward 1990; 2000; Goldingay and Sharpe 2004; Goldingay *et al.* 2007). These studies have demonstrated the importance of narrow cavity entrances which help to exclude larger species. These studies have also shown that feathertail gliders will use low nest boxes (3 m high) and that high densities can be achieved in small areas. In one survey Goldingay *et al.* (2007) recorded 24 adults and 20 subadults at one location across 6 nest box clusters spread across approximately 3 ha.

Feathertail gliders have been subject to short-term radio-tracking (2–8 nights) in southeast Qld (i.e. *A. frontalis*) (Kirk *et al.* 2000) and central Victoria (i.e. *A. pygmaeus*) (Ward 2004). These studies suggest home ranges might be of the order of 1–2 ha in area.

In summary, feathertail gliders prefer:

- live or dead hollow-bearing trees
- branch and trunk hollows equally
- hollow entrances of <3 cm diameter
- larger cavities with narrow entrances when they den communally

- multiple potential den trees, at a density of 1 per ha, given their home ranges may be equivalent in area to those of the greater glider.

Brushtail possum – Larger mammal species require large hollows and therefore large trees. The brushtail possum group includes the two mountain brushtail possums, one in northern NSW and another in southern NSW, as well as the common brushtail possum. They can be considered together. Surprisingly, the entrance size of the hollows they use has not been described. However, Inions *et al.* (1989) has described the details of trees used by 'possums' (which included the common brushtail possum and the western ringtail possum) in the south-west of Western Australia. The den trees were identified by obvious worn track marks on the trunk of a tree leading to a hollow, which indicated regular use by one of the two species. Of a subset of hollows that were measured (n=32) the diameters of the entrance and internal cavity were both 18 cm whilst the depth of the cavity below the entrance averaged 78 cm. Of these hollows 47% were in broken top trunks (i.e. vertical hollows), 28% were in the trunk, 22% were in broken branches and 3% were in a fork. The number of dens that were dead trees was not stated explicitly but 72% of 82 dens at one location 'were dead or in poor condition'.

Lindenmayer *et al.* (1991a) investigated the influence of the characteristics of trees occupied by mountain brushtail possums in the central highlands of Victoria. They found a negative influence of tree size, tree shape and the number of holes into the tree. Trees more likely to be occupied were basically shorter, stouter and with fewer hollows. A subsequent study (Lindenmayer *et al.* 1996) investigated the influence of the characteristics of den trees identified by radio-tracking with their frequency of use. In this analysis tree size and shape were not influential but this time the number of cavities (the sum of holes, fissures and hollow branches) had a positive influence on the frequency of use whereas tree access (a measure of dense vegetation around a den) had a negative influence.

Some of these apparent inconsistencies can be resolved by reference to the nest box literature. Brushtail possums readily use nest boxes (Harper *et al.* 2005; Le Roux *et al.* 2016). Nest boxes with entrance sizes of at least 10 cm and depth of at least 40 cm will be used at high frequency (Goldingay *et al.* 2020a). The high frequency of use suggests that these possum species will be readily catered for if trees provide hollows with entrances size of at least 10 cm diameter and a depth of about 40 cm.

The density and spacing of den trees was studied in detail for the mountain brushtail possum in Victoria ([1]Martin and Martin 2007). Depending on the location, possums used on average 7–17 dens within home ranges of 2–6 ha. In one forest habitat possums used an average of 1 den per ha ([1]Martin and Martin 2007). In road-side habitat where hollow-bearing trees were more abundant they used 3–4 per ha but this declines to 1 per ha if one only relies on the number primary dens (≥50% of records per individual) ([1]Martin et al. 2007).

In summary, brushtail possums prefer:

- relatively large hollows of at least 10 cm diameter and 40 cm depth
- trunk or branch hollows equally
- multiple potential den trees at approximately 1 per ha (Table 1).

Eastern pygmy-possum – Law *et al.* (2013) conducted a detailed radio-tracking study of this species. They found that possums denned frequently in tree hollows (41% of 543 unique dens), stumps (12%) and in fallen hollow logs (30%). A recent study has identified the critical importance of an adequate-sized cavity (~10 cm diameter) for maternity nesting and that this may influence the local abundance of this species ([1]Goldingay 2020). One nest box was the primary maternal nest. Non-breeding females, males and subadults have the capacity to use non-tree hollow shelters and narrow cavities (Goldingay 2020), which may lead to an over-estimation of den sites potentially available to maintain this species in an area (e.g. Law *et al.* 2013). Many studies with nest boxes have demonstrated a high use of cavities with a narrow entrance (<3 cm).

Home-range areas have been estimated to be 3–4 ha for animals tracked for an average of 7–9 weeks ([1]Law *et al.* 2013). All previous estimates were based on tracking periods of about 1–2 weeks which produced estimates of <1 ha and are considered unreliable estimates.

In summary, eastern pygmy-possums prefer:

- live or dead hollow-bearing trees
- branch and trunk hollows equally
- hollow entrances of <3 cm diameter
- a cavity of at least 10 cm diameter for breeding
- multiple potential den trees at approximately 0.3 per ha (Table 1).

Brush-tailed phascogale – This species may use a range of shelter sites, including sites other than tree hollows, outside the breeding period but during the breeding period females require a substantial cavity of at least 20 cm diameter (Soderquist 1993). This probably accounts for the frequent use of nest boxes in degraded habitat (Goldingay *et al.* 2018, 2020b). Home-range areas of females can be of the order of 30–50 ha on average over 1 – 3 months but areas of 5–13 ha are used more intensively and tend to be exclusive of other females (Soderquist 1995). Male home ranges are twice as large and overlap males and females. This species has been suggested to require a large number of cavities for nesting but this may reflect aspects of social behaviour and/or the location of studies with high hollow abundance (Goldingay *et al.* 2020b). Females begin to leave their young in the nest as they forage once the young get to 48 days of age ([1]Soderquist 1993). Consequently may use a single primary den for several months (Soderquist 1993; [1]Goldingay *et al.* 2020b; Thomas, K and Goldingay, R, unpublished observations) within the more intensively used area of up to 15 ha ([1]Soderquist 1995).

In summary, brush-tailed phascogale prefer:

- live or dead hollow-bearing trees
- branch and trunk hollows equally
- hollow entrances of <5 cm diameter
- a cavity of at least 20 cm diameter for breeding
- multiple potential den trees at approximately 0.1 per ha (Table 1).

Hollow-using bats

The tree hollow requirements of Australian cavity-using bats have been studied much less frequently compared to that of non-flying arboreal mammals. When reviewed in 2009 only 16 studies had been published (Goldingay 2009). Eight studies have been published since then that describe the roosts used by radio-tracked bats (Table 2). These studies highlight some flexibility in roost tree use by the species studied with several roosting under bark. Perhaps the most relevant point is the apparent need for large-cavity trees for maternal roosts. Bats are highly mobile and were usually captured >200 m from their first roosts and also moved >200 m between successive roost trees. The study by Lumsden *et al.* (2002) in Victoria highlights the mobility issue; *Nyctophilus geoffroyi* moved 2–7 km from their capture site to their roost site and *Chalinolobus gouldii* moved 4–10 km from their capture site to their roost site. This suggests these species, if not others, have the capability to find suitable roosting hollows across highly fragmented or altered landscapes and it is likely many other species do too as indicated by the studies reviewed below.

The study of Webala *et al.* (2010) was conducted in south-west (sw) WA and found that *Vespadelus regulus* and *Nyctophilus gouldi* roosted in tree hollows, though the latter also commonly roosted under bark and even under *Xanthorrhoea* leaf skirts. Roosts of the former species were located in mature forest or unlogged riparian buffers whilst roosts of the latter were located in riparian buffers, mature forest and remnant trees in shelterwoods. Both species chose large diameter trees (>80 cm DBH) for roosting. Bats travelled 340–465 m from capture sites to roost sites. No females were breeding when tracked. The study of Burgar *et al.* (2015) was also conducted in sw WA on *V. regulus* and *N. gouldi* but with a focus on restored forest following mining. These bats preferred large roost trees (>60 cm DBH). There were 59 roosts located, of which 15 were maternity roosts and all but two roosts were in hollows. Distances from capture sites to the first roost averaged 200–1830 m. All roosts were located in the remnant forest.

Table 2. Number of bat roosts located during radio-tracking in studies conducted since 2009.

Species	Roosts	Tree hollows	Reference
Vespadelus regulus	21	21	Webala *et al.* (2010)
Nyctophilus gouldi	27	9	Webala *et al.* (2010)
Nyctophilus geoffroyi	12	4	Law *et al.* (2011)
Scotorepens balstoni	5	5	Law *et al.* (2011)
Scotorepens greyi	5	5	Law *et al.* (2011)
Vespadelus vulturnus	6	6	Law *et al.* (2011)
Mormopterus norfolkensis	40	40	McConville *et al.* (2013)
Mormopterus norfolkensis	6	3 (3 unknown)	McConville & Law (2013)
Nyctophilus gouldi	41	24	Threlfall *et al.* (2013)
Nyctophilus gouldi	30	29	Burgar *et al.* (2015)
Vespadelus regulus	29	28	Burgar *et al.* (2015)
Nyctophilus corbeni	18	13	Law *et al.* (2018)
Nyctophilus geoffroyi	4	4	Law *et al.* (2018)
Nyctophilus gouldi	24	18	Law *et al.* (2018)
Vespadelus vulturnus	6	6	Law *et al.* (2018)
Nyctophilus gouldi	15	15	Rueegger *et al.* (2018)
Vespadelus vulturnus	16	16	Rueegger *et al.* (2018)
Scotorepens orion	6	6	Rueegger *et al.* (2018)

Law *et al.* (2011) radio-tracked four species to 28 roosts in an agricultural landscape on the Liverpool Plains of NSW. Four *Nyctophilus geoffroyi* roosts were under bark whilst other roosts were in tree cavities. Across the four species bats moved 60–590 m between roosts. No females were breeding when tracked. Law *et al.* (2018) radio-tracked four species to 52 roosts in the Pilliga forest of central-western NSW. This included one species, *Nyctophilus corbeni*, which had not had its roost trees documented before. Its requirements in that landscape were similar to those of *Nyctophilus gouldi*, with tree hollows and trunk fissures frequently used, and 30% of roosts being under bark.

Threlfall *et al.* (2013) radio-tracked *Nyctophilus gouldi* in an urban area of Sydney. Males and non-breeding females roosted under loose bark. The 19 maternity roosts were in tree trunks. The maternity roost trees were large (average DBH >60 cm) and a majority were in dead trees (53%). Bats moved an average of 165–225 m between roosts.

McConville and Law (2013) radio-tracked three *Mormopterus norfolkensis* in the Hunter Valley and three near Urbenville in north-east (ne) NSW. All were tracked to large roost trees (>65 cm DBH) but the roost type was not identified at Urbenville. Subsequently, McConville *et al.* (2013) radio-tracked *Mormopterus norfolkensis* to 40 roosts of which 36 were maternity roosts and contained an average of 8 individuals. These roosts were mostly located in mangrove forest on the Hunter River where there was a very high abundance of hollow-bearing trees.

The study by Rueegger *et al.* (2018) was conducted in a timber production forest on the NSW south coast and included three species (Table 2). Distances from capture sites to the first roost averaged 460–800 m. Distance travelled between roosts averaged 150–600 m. Maternity colony size varied from a mean of 14 for *N. gouldi* to 29 for *V. vulturnus*. The maternity roosts trees were large (average DBH >50 cm) and approximately 50% were dead trees. The majority (78%) of roost trees were located in riparian buffers.

In summary, hollow-using microbats prefer:

- live or dead hollow-bearing trees
- branch and trunk hollows equally
- hollow entrances of <5 cm diameter
- large DBH trees as maternity sites.

A landscape approach to roost and maternity tree retention should be applied given the long commuting distances that most bats are capable of.

Hollow-using birds

The species of interest here are the large forest owls, glossy-black cockatoo and the brown treecreeper. When the hollow requirements of the Australian hollow-using birds were reviewed in 2009 there had been two studies published describing the hollows of the glossy-black cockatoo, two for the powerful owl, one for the sooty owl, three for the masked owl, one for the barking owl and none for the brown treecreeper (Goldingay 2009). The average DBH of the nest trees across studies were: 70–99 cm for the glossy black-cockatoo, 130–163 cm for the powerful owl, 157 for the sooty owl, 137 cm for the masked owl and 120 cm for the barking owl. The only studies that described the entrance size of the nest hollows were one for the glossy black-cockatoo (25 cm diameter) and the one study of the barking owl (28 cm). The salient point here is the massive size of the trees selected as nest trees. This may partly reflect the abundance of old-growth forest where these species occurred but also may reflect that the large type of hollows favoured by these species may only be provided by very large trees.

Nest boxes have been installed for large owls and large parrots in NSW but none have been used by these species (Goldingay *et al.* 2020a). Nest boxes of a generalised design installed for the brown treecreeper have rarely been used (Goldingay *et al.* 2020a). However, one study has recorded 48 breeding events by brown treecreepers in vertically installed log hollows with entrance sizes of 4–15 cm and depths of 20–57 cm (Quin, Quin and Goldingay, in prep.). These values suggest that ensuring an adequate abundance of hollows for small and large gliders should also cater for this species.

The large owls are highly mobile species occupying very large home ranges. Area estimates will vary with habitat quality as well as the duration of the study and are based on relatively small sample sizes, but commonly the areas are of the order of 500 ha to >1500 ha. The powerful owl has been the best studied with home ranges of females averaging 500–1700 ha and for males 1300–2300 ha (Soderquist and Gibbons 2007; Bilney 2013; Bradsworth *et al.* 2017). For the sooty owl home ranges of females in East Gippsland averaged 1000 ha and males 3000 ha, and it was suggested that sooty owl management areas, where logging is excluded or restricted, should be at least 1000 ha in size (Bilney *et al.* 2011). Kavanagh and Murray (1996) estimated the home range size of one masked owl as 1000 ha.

The implication of these large areas in relation to tree hollows is that very large hollow-bearing trees are unlikely to be limiting at the landscape scale for these highly mobile owls. The more important implication might relate to whether tree hollow abundance limits the abundance of preferred prey species such as possums and gliders. Glossy-black cockatoos are also quite mobile and should be able to find a sufficient number of hollow-bearing trees at the larger spatial scale at which they move given general logging exclusions across production areas.

Research gaps

Although our knowledge of tree hollow selection and use by mammals and birds is incomplete there is sufficient information to guide the management of this ecological resource. For example, we know the cavity entrance sizes that are favoured by different species and we know that most if not all species show flexibility in their choice subject to their body size constraints. Probably the largest gap is around matters relating to den tree persistence and attrition. This includes the attrition or creation of hollow-bearing trees during and following wildfire. Only a relatively small number of studies have been conducted and they are somewhat idiosyncratic because they have occurred in climatically different bioregions (Table 2) with different management histories. These are summarised below. Many further studies of hollow-bearing tree attrition following logging are required.

Table 3. Summary of studies that investigate the effects of fires on hollows and hollow-bearing trees (HBTs). Inions *et al.* (1989) specifically recorded HBTs used as possum dens.

Response to fire	Location (State)	Reference
Increase in den tree abundance after fire	sw WA	Inions *et al.* (1989)
More HBTs with increasing time-since-fire	se Qld	Eyre *et al.* (2010),
	Murray mallee	Haslem *et al.* (2012)
Fewer hollows with more fires	montane ACT	Salmona *et al.* (2018)
More hollows with higher fire severity	montane ACT	Salmona *et al.* (2018)
More hollows with more fires	ne NSW	McLean *et al.* (2018)
Loss of dead HBTs with fire	sw WA	Inions *et al.* (1989),
	se Qld	Eyre (2005)
	se Qld	Eyre *et al.* (2010)

A study in the south-west of Western Australia recorded a substantial increase in den trees (2.3/ha to 7/ha) used by possums following a high intensity prescribed fire in a study area of 35.6 ha (Inions *et al.* 1989). Den trees were identified by the presence of obvious track marks on the trunk of a tree leading to a hollow, indicating regular use by one of two possum species (the common brushtail possum or the western ringtail possum). The assumption is that the track marks reflect use of the available resource and any increase or decrease over time reflects a change in the abundance of the hollow resource. A reference site (21.5 ha in area) showed essentially no change in the abundance of den trees (3.4 to 3.1/ha) over the same period. This study lacks replication but provides a useful case study because there are few studies attempting to investigate changes in hollow abundance following fire. At the reference site average den tree DBH was 95 cm. At the burnt site before the fire den tree DBH averaged 83 cm whereas after the fire it was 70 cm. The fire led to 37% of den trees being destroyed or becoming unusable. The reduction in den tree DBH suggests it was the larger trees that were more likely to be lost. At the burnt site 59 (72%) of 82 den trees were dead or in poor condition whereas after the fire 172 (68%) of 254 den trees were in such condition, suggesting the fire had killed many trees. Many (44%) of the dead trees were destroyed by the fire. The increase in hollow abundance after the fire may reflect that many trees were very old and had internal cavities that the fire was able to create openings into. Such a scenario may not prevail elsewhere so assumptions should be carefully assessed.

In semi-arid south-east (SE) Australia, Haslem *et al.* (2012) found an increase in hollow-bearing tree abundance with increasing time since fire; longer fire-free periods were associated with a higher density of hollow-bearing dead stems. In a montane forest of SE Australia, Salmona *et al.* (2018) investigated the influence of the number of fires and a wildfire in 2003 on hollow abundance in alpine ash (*Eucalyptus delegatensis*: killed by fire) and snow gum (*E. pauciflora*; resprouts after fire). They found that the total number of hollows decreased in both species with an increase in the number of fires but that the 2003 fire led to an increase in hollows. Dead trees had a higher chance of containing a hollow and showed a substantial reduction as fire intensity increased.

In subtropical NE NSW, McLean *et al.* (2018) also identified some complex patterns. Logging and fire frequency combined to produce fewer hollows. Whereas, on unlogged plots fire was positively correlated with hollow abundance.

Monitoring of tree hollow use and relevance to hollows in areas subjected to logging

Several methods have been used to monitor the use of tree hollows by mammals and birds: i) radio-tracking, ii) trapping on trees with hollows, iii) detection of tree-use scratch marks, iv) direct hollow observations, v) remote cameras, vi) ultrasonic bat detectors. To this could now be added: vii) hollow observations with a thermal camera. The previous use of these methods to monitor hollow use by mammals and birds is outlined below and based on that a summary is provided in which the advantages and disadvantages of each method is given (Table 4). This is followed by recommendations of which methods are likely to be the most productive in broad-scale monitoring.

i) Radio-tracking has been used extensively to locate animals in their tree hollows (e.g. Kehl and Borsboom 1984; Lunney *et al.* 1988; Lindenmayer *et al.* 1996; Rhodes and Wardell-Johnson 2006; Penton *et al.* 2020). This method has contributed more than any other single method to our understanding of factors that influence the frequency of use and selection of tree hollows. It is a labour-intensive method that relies on being able to capture individuals of the target species to which transmitters are attached.

ii) Trapping on trees with hollows (Smith 1984; Cockburn and Lazenby-Cohen 1992). This is a very specific method to evaluate the use of nest trees. One of the best examples of this method is that by Smith (1984) who installed traps on horizontal brackets on potential den trees of Leadbeater's possums, with eight reached by ladders constructed directly on the trees up to heights of 7–20 m. Cockburn and Lazenby-Cohen (1992) placed traps on brackets on trees to identify use by brown antechinus. This method is very labour-intensive and probably only relevant in specific cases.

iii) Tree-use scratch marks (Inions *et al.* 1989; Koch *et al.* 2018). When animals use trees frequently, they leave wear marks (scratch-tracks) from repeated climbing over the bark with their sharp claws. Repeated entry and exit from tree hollows may also leave a pronounced wear mark around the edges of a hollow. These marks of use can be used to provide data on patterns of tree hollow use. One key limitation is that although wear marks may be scored for their apparent intensity of use (very good to poor tracks), a long intervening period or fire is needed to enable a temporal comparison of use. Another is that tracks are likely to be much more apparent and longer lasting on rough-barked trees compared to smooth-barked trees that may not mark as readily and will shed their bark annually.

iv) Direct hollow observations (Smith 1984; Pell and Tidemann 1997; Law *et al.* 2000; Rhodes and Wardell-Johnson 2006; Threlfall *et al.* 2013). This method can be applied day or night. The method has become a standard method for sampling Leadbeater's possums and other arboreal mammals in the central highlands of Victoria when applied to stags (standing dead trees) at dusk (Lindenmayer *et al.* 1991a). This method has also been applied to investigate the use of paddock trees (Law *et al.* 2000). Tree hollows may have low rates of use in some areas so many trees may need to be observed to record use. Direct diurnal observation has been used successfully with repeat visits to sample individual trees during the bird breeding season when activity around hollows may be relatively high (Saunders *et al.* 1982; Pell and Tidemann 1997; Threlfall *et al.* 2013).

v) Remote cameras directed at tree hollows. This method has only been used in two studies. In one (Davis *et al.* 2013, 2014), cameras were installed at 61 hollows by using ropes to climb trees. Twenty species of hollow-using mammals and birds were identified. In the other (Cotsell and Vernes 2016), cameras were installed using an elevated work platform (ELP). Despite the limitations associated with the ELP 63 hollows were monitored across 8 locations for up to 80 days. There were 38 species recorded visiting the hollows including many hollow-dependent mammals and birds. Some differences in visitation were found among different tree species. Although cameras have been rarely used in Australia to monitor tree hollows, they have been used to monitor visitation to nest boxes (Rueegger *et al.* 2012). The use of cameras to monitor hollows is potentially powerful but may be limited by the need to use arborists or ELPs to install cameras at appropriate locations.

vi) Thermal cameras have begun to be used for night-time surveys of wildlife (Augusteyn *et al.* 2020; Vinison *et al.* 2020). These early trials suggest they have the ability to detect more animals compared to spotlights. If they are trained at tree hollows at dusk they are likely to detect animals more readily than monitoring in available night light. There is likely to be a distance range over which they are most effective and this will vary with body size. Trials are needed to test out the relative merits of this method and to determine how restrictive the number of cameras would be. It's likely only a small number of hollows could be monitored per night whereas the traditional stag watching technique has used volunteers to increase the number of trees monitored concurrently.

vii) Ultrasonic bat detectors to record bat activity near hollows. This method was developed by Law *et al.* (2000). Bats emerging from hollows after dark will not be observed. However, bat passes recorded by detectors cannot be specifically aligned with hollow use. There may be a height limitation to detection. Nonetheless, detection of species within a hollow-bearing tree provides evidence of that tree having some value. Repeat surveys at the same trees could reveal patterns of use.

Recommendations for methods to monitor hollows

All methods had some advantages and some disadvantages (Table 4). The best results in terms of obtaining data are likely to arise from combining a couple of the methods. Direct observation of hollows has particular merit due to being able to monitor several hollows at once and to easily replicate across many sites. Diurnal observation of hollows could be conducted without many constraints. Repeat visits to the same hollows will be needed to account for an expected low rate of detection and would allow data to be analysed using an occupancy framework. Observations should be conducted during spring when birds are most likely to be breeding and frequently moving to and from nests.

Table 4. A brief evaluation of different methods used to monitor the use of tree hollows.

Methods	Advantages	Disadvantages
Radio-tracking	No ambiguity about current use. Various species can be sampled.	Labour-intensive. Sample size may be low due to the need to trap animals and attach transmitters.
Tree-trapping	Provides age-sex data for captured animals. May provide data for many individuals using hollows.	Labour-intensive. May provide few data relative to effort. Captured animals might not be using hollows.
Tree-use scratch tracks	Very low cost. Only binoculars required. Large sample size of trees surveyed.	Some tree species unsuitable. Animal species making the tracks unknown. Small species may produce less wear and be overlooked. Birds may be under-sampled.
Direct observations	Very low cost. Only binoculars required. Large sample size of trees surveyed. Can be applied day or night to sample birds and mammals.	May require a large amount of effort to obtain any data.
Remote cameras	Long periods of monitoring. Can operate day and night.	Requires climbing trees or using elevated work platforms to install cameras.

		Sample sizes limited by equipment and access to hollows. Safety issues will preclude monitoring of some/many hollows.
Thermal cameras	May provide more reliable nocturnal sampling.	Unproven reliability. Equipment is very expensive. Limited equipment availability will limit sample sizes. Small species unreliably sampled.
Ultrasonic detectors	May provide abundant data on hollow-using bats.	Data may not accurately reflect hollow use. May be some limitation to the distance of detection.

Nocturnal observations could be conducted at dusk and supported by the use of thermal cameras. The availability of cameras may limit the ability to collect a large data set. Bat detectors could also be used for a limited period after dark to provide an index of potential use. Data should be collected from repeat visits and analysed using an occupancy framework.

Visual observation to identify wear marks around hollows also has much potential because it would allow many hollows to be evaluated for use over a short period. Although the species using the hollows won't be known indices of the relative use of different hollow sizes in different tree species could be collected. However, this is a method requiring calibration because wear marks may be evident for an extended period after a hollow was last used. If hollows are monitored in retained trees following logging there needs to be certainty that use has occurred post-logging.

The method likely to produce the most reliable data is the use of remote cameras but this method has the most limitations due to an inability to install cameras wherever monitoring is needed. This method could be applied at a small number of locations where there is suitable access for an ELP. The data generated could be used to calibrate the data collected from other methods.

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