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Aspects of the foraging and roosting ecology of the large-eared pied bat (*Chalinolobus dwyeri*) in the western Blue Mountains, with implications for conservation

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Abstract. The large-eared pied bat (*Chalinolobus dwyeri*) is listed as vulnerable at both state and federal level, yet little is published on its foraging ecology. Research was conducted to examine its foraging range and habitat (foraging and roosting) preferences. Seven individuals (five female and two male) were radio-tracked in the Blue Mountains, New South Wales, on two separate occasions over a total of nine tracking nights. Females had larger foraging areas than males, but both showed high fidelity to preferred foraging areas. Females roosted separately from males, showing less roost fidelity and roosting at a greater distance from the foraging area. Both males and females roosted in west-facing cliff faces without large caverns. The preferred foraging area included: a sharp grassland–forest border in a western-facing valley, a creek or moist drainage gully with wet vegetation types and day roosts within 700 m. At the fine scale, bats foraged along forest edges at mid-to-upper-canopy height and on the outer canopy of individual trees within the forest. Our data suggest that the presence and distance of such habitat requirements should be considered when assessing land management and conservation activities.

Additional keywords: foraging range, microbats, roost fidelity.

Introduction

Global biodiversity is in decline and Australian mammals are no exception. Of the 273 endemic terrestrial mammals that have inhabited Australia, 11% are extinct, 21% are threatened and 15% are near threatened (Woinarski *et al*. 2015). Protection and management of threatened species is difficult, as biological information for many Australian species is incomplete (Woinarski *et al*. 2014). One such data-deficient species is the large-eared pied bat (*Chalinolobus dwyeri*).

The distribution of the large-eared pied bat includes eastern Queensland and New South Wales, in areas with volcanic rock and sandstone outcrops and escarpments for day roosting and maternity sites (DERM 2011). This habitat specialisation is a major factor in the species' conservation status, being listed as near threatened under IUCN criteria and vulnerable at Australian state and federal level (i.e. *Biodiversity Conservation Act 2016*, *Queensland Nature Conservation Act 1992*, and *Environmental Protection and Biodiversity Conservation Act 1999*). Despite this conservation status, the major threats to the species are not well established; indeed, the only confirmed threat is the destruction of, and/or interference to, maternity roost sites (DERM 2011). Other proposed threats include mining of roosts, mine-induced subsidence of clifflines, vegetation clearing, and disturbance by recreational caving, fire, pests and farming animals (DERM 2011).

The uncertainty of known threats stems from a lack of knowledge on *C. dwyeri*. Specifically, one of the major objectives in the national recovery plan is for further research into the ecology of the species, particularly relating to habitat requirements (foraging and roosting), population distribution, diet and foraging strategies (DERM 2011). Three aspects of the species' ecology were examined in this short-term study: (1) day roost locations (by radio-telemetry), (2) foraging range (radio-telemetry), and (3) foraging habitat (radio-telemetry, echolocation recorders and light tags).

Materials and methods

Study site

This study was undertaken in the Mugii Murum-ban State Conservation Area and adjacent agricultural land in the western Blue Mountains, New South Wales (–33.101676°S, 150.027856°E) (Fig. 1). The conservation area is dominated by a range of vegetation types, which can be broadly categorised as dry eucalypt forests on the sandstone plateaux (>1100 m elevation) and talus slopes, wet forest/riparian in creeks, drainage gullies and gorges, and heath shrubland on dry pagoda

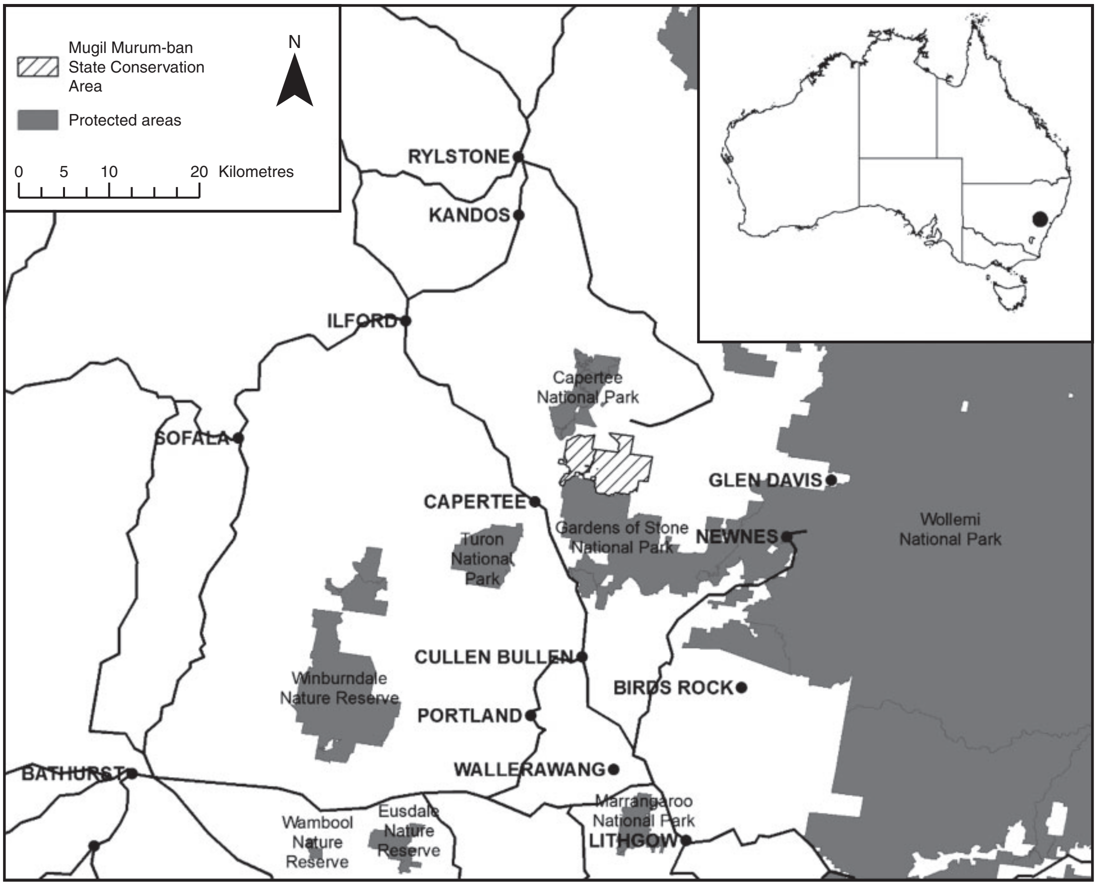

Fig. 1. The primary study location at Mugii Murum-ban State Conservation Area in the western Blue Mountains.

formations. The adjacent agricultural land (~730 m elevation) was historically cleared for cattle grazing, with isolated woodland fragments typically in creek lines and on hill crests. Average annual rainfall for the area is 814 mm (last two decades, Running Stream weather station: BOM 2015). Microbats were trapped with a harp trap at a night roost in an abandoned mine frequented by *C. dwyeri* as detected by previous monitoring activities. Trapping and radio-tracking were conducted between 20 and 28 October 2014 and between 12 and 19 December 2014.

Radio-telemetry

Seven individual *C. dwyeri* were radio-tagged, including two males and three non-parous females (potential gestation period: Dwyer 1966) in October, and two non-parous females in December (postbirthing season). Radio-tags (LT6-337 with a 150-mm two-strand aerial: Titley Scientific, Brendale, Australia) weighed 0.47 g ($\leq$5% bat body weight; as per Aldridge and Brigham 1988) and had increased pulse width to allow for detection at greater distances in the complex terrain at the study site. Transmitters were attached to untrimmed fur between the shoulder blades with a flexible, water-based glue (Selleys Kwik Grip Waterbased, Padstow, Australia) before bats were released in the vicinity of the capture site.

To locate roost rock faces (four days in October, five in December), the study area was traversed on foot during daylight with two three-element directional yagi antennae (Sirtrack Electronics, Havelock North, New Zealand) and receivers (either ATS R2000, Isanti, USA or Telonics TR4, Mesa, USA). Reflection of the transmitter pulse in the large sandstone escarpments and rock pagodas meant that precise roost locations could not be determined; however, the general area (i.e. rockface – upper or lower portion) could typically be determined due to a far greater signal strength detected. Coordinates and aspect of the suspected roosts were recorded and photographed.

Nocturnal foraging locations were determined by two methods. Primarily, two directional yagi antennae and receivers were used simultaneously to record the bearing and signal strength of tagged bats from separate base stations (coordinated with two-way radios for precise recording times). Triangulations of bat positions were calculated from the two base stations and bearings in QGIS (QGIS Development Team 2015) with the Animove plug-in (http://www.faunalia.eu/en/animove.html). Because of topographical or technical difficulties, at times only one yagi antenna and receiver were used to record bat positions. In these circumstances, distances to tagged bats were estimated on the basis of signal strength. Specifically, analyses of signal strength and known distances from triangulation data calculated a logarithmic association ($r^2 = 0.969$) (Fig. 2), although the few positions with low signal strength resulted in high variation. As such, low-signal

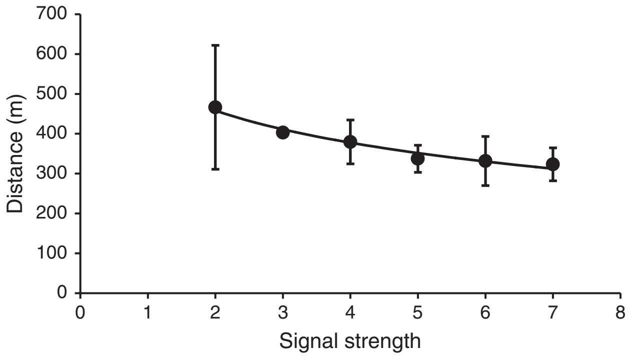

Fig. 2. Location points from single yagi antenna observations were computed based on the logarithmic association calculated from signal strength and distance from triangulation data.

observations from a single yagi antenna were omitted from analyses.

Nocturnal radio-tracking was conducted in October (four nights) and December (five nights) for a minimum of 3 h after sunset (when bat species are most active: Law *et al*. 1998), except during incoming storms ($n = 2$; typically short disruptions), and at various locations surrounding the day roosts or foraging locations determined by previous monitoring activities (e.g. Williams *et al*. 2014). During radio-tracking, each bat frequency was checked sequentially and repeatedly, thus taking positional data for every (present) bat at ~5-min intervals. An exception was when individuals alighted from diurnal roosts towards foraging sites ('commutes'), where positions were recorded more frequently (<5–60 s).

Flight data points were used to estimate foraging range (FR) (based on the 95% isopleth; i.e. probability of relocating the animal in the area is 95%) and core use area (CUA) (50% isopleth) separately by sex and survey month (all nights per individual). Both measures were used to identify smaller localised foraging areas within greater home ranges (Kunz and Lumsden 2003). Although using an arbitrary boundary such as the 50% isopleth for CUA has limitations (Goldingay 2015), it is widely used in home-range studies. FR and CUA were calculated by the Kernel Density Estimate function in ArcMap (ESRI 2011), RStudio (RStudio Team 2015) and Geospatial Modelling Environment (Beyer 2012) with a least-squares cross-validation method for smoothing. Foraging density, to identify highly used areas, was determined by overlaying polygons of observed daily points for all seven individual bats from both seasons.

Echolocation recorders and light tags

In December, passive echolocation recorders (SongMeter SM2+ Bat, Wildlife Acoustics, USA) were placed along a transect across the forest edge in an area where previous radio-telemetry triangulations had confirmed *C. dwyeri* activity. These data were used to provide independent cross-checking of the positions calculated with concurrent radio-telemetry. Recorders were positioned for three consecutive nights at 50 m into forest (–50 m), at the forest/grassland edge (0 m), 50 m into the grassland (+50 m) and 100 m into the grassland (+100 m). To estimate the distance at which the recorders could detect *C. dwyeri*, a captive bat was held at varying distances from the recorders and subsequent analysis of sonograms showed that bats were only detected at less than 10 m from the recorder, suggesting that calls recorded during the night were passing close to each echolocation recorder on the transect. Call data were analysed to determine the number of passes by *C. dwyeri* per night, with individual passes demarcated by a 2-s gap between calls.

Cyalume light tags (e.g. Neptune Tackle light sticks, Port Adelaide; 45 mm × 3.9 mm, ~0.56 g) were attached ventrally with a small dab of the above-mentioned adhesive (for rapid detachment) to three non-parous females (not used in radio-tracking) in October and released at the forest edge near capture. Bats were followed for as long as possible (with binoculars and a spotlight used to determine height/position in canopy) and searched for during the following 4 h. As bats immediately started foraging behaviour at the forest edge (slow circling flight with fast dipping down to capture insects), it is assumed that the light tags or spotlight did not alter typical behaviour.

Results

Spatial foraging

In total, 165 telemetry fixes were recorded, of which 77% were for foraging range (37% triangulation, 40% single yagi antenna) with the remaining fixes being at roosts or commutes between day roosts and foraging areas. Males (29% of tagged individuals with 33% total fixes) were recorded slightly more often than females.

The mean short-term FR and CUA were larger for females in October (Table 1), with the CUA approximately double that of males. In December, one of the two females (F5) had low values of both CUA and FR, potentially due to the low sample size of foraging points ($n = 9$). The other December female (F6) had similar CUA and FR to the October females, and more foraging observations ($n = 26$). Plotting cumulative polygon areas over time for each bat showed that the data for males reached an asymptote, whereas those for females did not (data not shown).

Regardless of sex or survey month, all individuals overlapped in FR in a west-facing valley (Fig. 3). An area where the CUA of three or more bats overlapped was determined to be a 'high use area' and was used frequently in both October and December. However, on several nights, one or more individuals could not be located from vantage points within a 2-km radius of the valley. Specifically, of the 20 bat-tracking opportunities in October (5 bats × 4 nights), there were five occasions where individuals were not detected. In December, with 10 opportunities (2 bats × 5 nights), both females were absent on Night 2 and one female on Night 5. Additionally, there were times when bats were located during only part of the night.

The vegetation in the forested part of the high-use area is broadly classified as wet sclerophyll forest (as per vegetation data by DEC 2006) and is the largest of this kind adjoining grassland in the immediate area, which typically consists of drier vegetation types. The area contains permanent small water pools (E. Williams, pers. obs.), is a sharp transitional zone between forest (wet and dry) and grassland, is within a

Table 1. Core use area (CUA) and foraging range (FR) of tagged *C. dwyeri* in the western Blue Mountains

n, no. of telemetry positions

Bat	*n*	Area (ha)		Maximum distance from roost (m)	
		CUA	FR	CUA	FR
Males: October					
M1	36	14.7	73.1	569	787
M3	15	14.3	69	724	930
Mean (s.e.)		14.5 (0.2)	71 (2.1)	646.5 (77.5)	858.5 (71.5)
Females: October					
F0	16	29.5	115.6	1208	1380
F2	13	29.7	145.6	1701	2489
F4	12	26.9	92.5	1172	1459
Mean (s.e.)		28.7 (0.9)	118 (15.4)	1360.3 (170.7)	1776 (357.2)
Females: December					
F5	9	6.1	21	1005	1227
F6	26	25.7	100.6	2144	2751
Mean (s.e.)		15.9 (9.8)	60.8 (39.8)	1574.5 (569.5)	1989 (762)

western-facing valley and contains shallow abandoned mine adits (used as night roosts: Williams *et al*. 2014).

Day roosts

All day roosts were in rockfaces along sandstone escarpments either overlooking the main foraging area or ~600 m to the north-east. Cliff faces where bats roosted were flat, vertical walls 10–15 m high with only small fissures (maximum ~30 cm high) (e.g. Fig. 4). No tagged bats were obvious when inspected from the ground, from nearby rock platforms or with binoculars. The rockfaces of these day roosts were all western facing ($\mu = 265°$, range = 191–313°), with roosts of females typically more directly west ($\mu = 273°$) than those of males ($\mu = 241°$).

In October, the two males roosted within 185 m of each other and more than 650 m from the three females (see Fig. 3). Male roosts were within the high-use area and showed a degree of site fidelity (e.g. they were located on the same cliff face on several consecutive days). In contrast, females were rarely in the same cliff line on consecutive days (although they may have returned on later days) and often were not found during day searches. Specifically, only 50% of female roosts were found in October and 60% in October despite searching within 2 km of the high-use area, although this may have been influenced by the complex terrain.

Fine-scale foraging movement

On release, all three bats with light tags flew with a slow fluttering flight, and foraged predominantly along the forest edge at mid to upper canopy height ($\geq$6 m). Later observations showed bats circling around the outer edges of tree canopies from low to upper slopes in the valley. Bats seldom flew into the tree crown foliage. While foraging along the outer edge of trees, all three bats made rapid downward dives, presumably to capture prey. They were adversely affected (appeared to be 'blown' off course) by moderate to strong wind gusts.

The echolocation recorders showed that bat activity at the forest edge (0 m) was 24 times greater than in the grassland and forest ($H = 7.92$, $P = 0.047$) (Fig. 5). Fewest passes were observed within the forest. Feeding buzz data showed similar patterns but at lower values (data not shown).

Discussion

This is the first published study to examine roosting and foraging habitat of *C. dwyeri* using radio-tracking. In the western Blue Mountains, radio-tracking revealed that day-roosting occurred within 700 m of the foraging area. The maximum distance between a known roost and the edge of the preferred foraging area was 2.5 km on a single occasion. Both roosts and foraging areas were located in a western-facing valley with natural forested vegetation in the upper parts and cleared pasture in the lower sections. Light tags and ultrasonic recorders revealed that it was along this forest/pasture boundary and in adjacent forest/riparian areas that bats foraged.

Radio-tracking with identical methods in a secondary location (Lamington National Park, Queensland; –28.221842°S, 153.120321°E) was attempted on 24–29 January 2016 (authors' unpubl. data). However, only one non-parous adult female was trapped, radio-tagged and tracked over three nights. As in the Blue Mountains, foraging was concentrated in a sharp transition between forest/riparian vegetation and grassland, and within 700 m of the day roost (a westward-facing cliff face with no caverns visible).

Roosting requirements

Although often site- and habitat-specific, the pattern of roosting close to foraging areas by both sexes is more pronounced in this species than in other Australian *Chalinolobus* species, such as *C. morio* (>20 km: B. Thomson, unpubl. data) and *C. gouldii* (6.9 km: Lumsden *et al*. 2002). This study also indicated the exclusive use of crevices in vertical, sheer cliff faces for day roosts by male and non-parous females. No tree roosts were identified.

All bats roosted in sandstone cliff faces without cave or cavern development. This accords with other observations for the species in non-reproductive condition (caves and caverns are known to be used during the maternity period: DERM 2011). Although cliff faces were present at all cardinal directions in

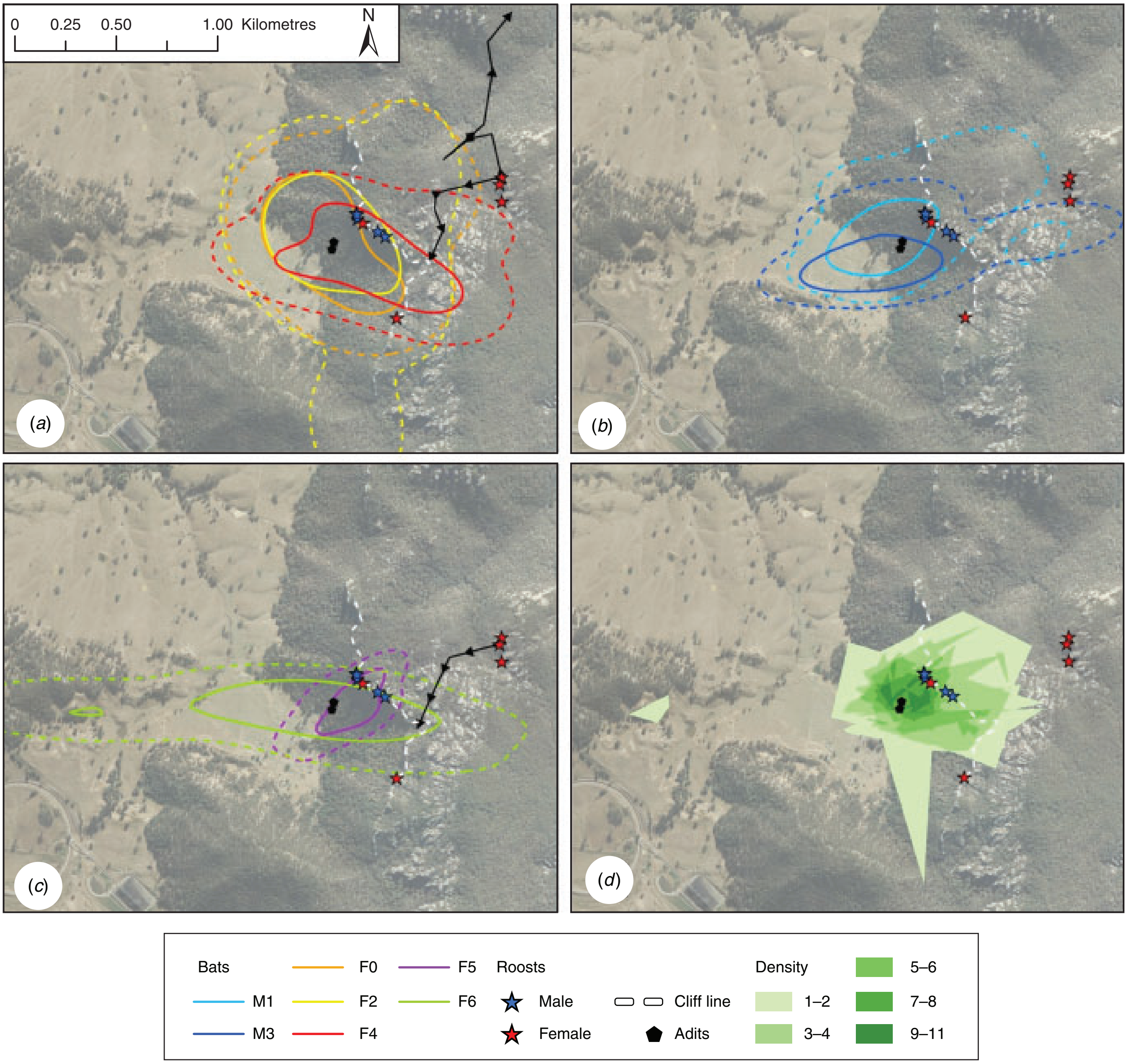

Fig. 3. Foraging range (dashed coloured lines) and core use area (solid coloured lines) of *C. dwyeri* for: (*a*) females in October (all days combined), (*b*) males in October, (*c*) females in December, and (*d*) foraging density (daily observed polygons of all bats).

the study area, *C. dwyeri* roosted in clifflines facing south-west to north-west. The selection of these roosts may confer thermoregulatory benefits to the roosting bats. Specifically, western-facing roosts would remain cool during the early to middle part of the day (facilitating torpor), but act as heat sinks in the late afternoon to assist in passively warming bats before emergence (Vaughan and O'Shea 1976; Chruszcz and Barclay 2002).

For many species, roost choice is thought to be influenced by the abundance of roosts, the distribution and abundance of food, social organisation and energetic considerations relating to body size, flight morphology and the physical environment (Kunz 1982; Kunz and Lumsden 2003). The bats in our study showed almost daily roost changes; however, they typically stayed close to the preceding roost, especially males. Fidelity to localised roost areas or a cluster of roosts (rather than to an individual roost) is known in Australia and elsewhere (Kunz 1982; Lunney *et al.* 1988; Kunz and Lumsden 2003). This provides the benefits of roost fidelity (site familiarity, maintenance of social relationships, retention of maternity sites) whilst minimising the costs (increased energetic costs with commuting to locally changing food sources, increased predation/parasite/pathogen risk in returning to the same crevice: Lewis 1995).

Fig. 4. Examples of rockfaces where females (left) and males (right) were day roosting in October 2014. Photographs by E. R. Williams.

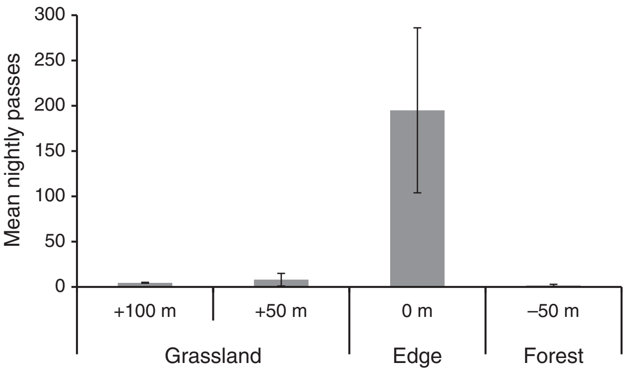

Fig. 5. Mean nightly (±s.e., $n = 3$) bat echolocation passes recorded over a transect across the ecotone from forest to grassland.

Foraging range and core use area

In the western Blue Mountains, there was substantial overlap in the main foraging areas (both FR and CUA) of individuals. Males had a smaller CUA and FR (14.5 and 71 ha, respectively) than non-reproductive females (28.0 and 113.6 ha). These short-term FRs of *C. dwyeri* were greater than those of several other Australian vespertilionids for which published short-term data are available, including the eastern forest bat (*Vespadelus pumilus*) (4.1–6.2 ha: Law and Anderson 2000), the little forest bat (*V. vulturnus*) (14–35 ha: Gonsalves *et al*. 2013), the southern forest bat (*V. regulus*) (<10 ha: Churchill 2008) and the eastern cave bat (*V. troughtoni*) (33 ha: Churchill 2008). However, considering tagged *C. dwyeri* individuals were absent on several occasions during radio-tracking, it is possible that absolute foraging ranges were larger than we recorded.

At the preferred foraging area, the presence of diverse vegetation (grassland, dry and wet forest) and nearby water bodies are likely to provide conditions that support increased invertebrate density and diversity. For example, varied food and habitat resources allow for different invertebrate life stages, including aquatic larvae (Tidemann and Flavel 1987; Entwistle *et al*. 1996; Grindal and Brigham 1999; Lumsden *et al*. 2002). Western-facing cliffs may heat during the afternoon, and then retain and radiate heat in the hours following sunset. This may assist the bats in thermoregulation, discussed above, and also benefit nocturnal insects in the first hours after darkness, which is typically when insect and bat activity peaks (e.g. Kunz 1973; Taylor and O'Neill 1988; Entwistle *et al*. 1996; Hayes 1997).

The fine-scale foraging patterns observed in this study may be due to energetic constraints. Optimal foraging theory by Stephens and Krebs (1986) predicts that animals maximise their net energy gain by selecting foraging areas where prey encounters are highest and energy expenditure lowest. In various studies, forest edges and isolated trees or fragments provide a more efficient foraging habitat with both accessibility (i.e. ease of foraging in a habitat) and higher prey availability (Brigham *et al*. 1997; Grindal and Brigham 1999; O'Donnell 2000; Lumsden *et al*. 2002). This study supports such findings, with higher echolocation activity of *C. dwyeri* along forest edges.

Additionally, flight behaviour is known to influence home-range size and foraging strategy (Fenton 1972; Rhodes 1995). Species with low wing loading (such as *C. dwyeri*) typically have a slow, highly agile flight (Fenton 1972; Arita and Fenton 1997), which is more suited to foraging around, but not within, vegetation clutter (Norberg and Rayner 1987). This is supported in our study: *C. dwyeri* was observed to have a slow, fluttery flight, and foraged in the mid to upper canopy along the forest edge or around tree crowns on the slopes. This flight behaviour, including the dipping flight path to capture insects, has been observed in other bat species with low wing loading (Entwistle *et al*. 1996; Lumsden *et al*. 2002).

In contrast, we also observed *C. dwyeri* commuting at fast speed between roost and the preferred foraging area (~600 m in <10 s). Rapid commutes between roosts and/or foraging areas has been recorded in other studies (Lumsden *et al*. 2002; Rhodes and Catterall 2008) and is thought to minimise predation risk and simplify navigation (Entwistle *et al*. 1996).

Implications

When considering the conservation of a threatened species, it is important to understand the use of landscape mosaics, including forest edges, fragments and isolated trees (Lumsden *et al*. 2002). This is pertinent for *C. dwyeri*, particularly as vegetation clearing is widespread within its distribution and is a major threat to the species (DERM 2011). Although *C. dwyeri* often foraged along forest edges or fragments in our study, this is only one factor in the conservation of the species: food availability and roosting requirements are also important considerations.

As limited information is published on the roosting and foraging ecology of *C. dwyeri*, further validation at other locations with more tagged individuals is required, as well as incorporating research on precise roosting locations and foraging range. Additionally, as no maternity caves or parous females were found in this study, the roosting and foraging requirements of breeding *C. dwyeri* is yet to be described.

As various Australian bats show considerable fidelity to roosts (Law 1995), it is imperative to consider whether a species consistently returns to particular foraging or roosting sites when assessing the sensitivity of a species to disturbance. In our study, *C. dwyeri* showed a degree of fidelity to a roost area(s) and preferred foraging areas. Indeed, the proximity and frequent return to the same foraging area for all the tagged individuals in our short study may suggest that *C. dwyeri* is more susceptible to habitat loss at the local scale compared with more generalist species or those with larger FRs.

Conflicts of interest

The authors declare no conflicts of interest.

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