

Tracking movement, home range, and microhabitat use in a small terrestrial breeding frog using harmonic direction-finding technology

Jordy Groffen^{A,*} , Conrad J. Hoskin^A, Matthew S. Siderhurst^B and Myles H. M. Menz^{A,C} 

For full list of author affiliations and declarations see end of paper

*Correspondence to:

Jordy Groffen
College of Science and Engineering, James
Cook University, Townsville, Qld 4811,
Australia
Email: Jordy.Groffen@my.jcu.edu.au

Handling Editor:

Adam Stow

Received: 8 July 2024

Accepted: 21 June 2025

Published: 15 July 2025

Cite this: Groffen J *et al.* (2025) Tracking movement, home range, and microhabitat use in a small terrestrial breeding frog using harmonic direction-finding technology. *Wildlife Research* **52**, WR24111. doi:10.1071/WR24111

© 2025 The Author(s) (or their employer(s)). Published by CSIRO Publishing.
This is an open access article distributed under the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND).

OPEN ACCESS

ABSTRACT

Context. Tracking the movements of an animal increases our understanding of its behaviour and ecological preferences. **Aims.** This study aimed to assess the movements, home range, nesting sites, and microhabitat use of a very small, cryptic, terrestrial microhylid frog species (*Austrochaperina robusta*) in an upland rainforest, during the breeding season. **Methods.** We used harmonic direction-finding (HDF) technology with ultra-light harnesses/tag combinations of two sizes (small 0.023 g and large 0.033 g) to track male *A. robusta*. These are substantially lighter than all tag/harness combinations previously used in amphibian tracking studies and represented a small proportion (1.8–2.58%) of the body mass of the very small study species, *A. robusta* (1.27 ± 0.20 g). **Key results.** Both tag sizes were effective for tracking, and tag size did not change the distance moved or time until an individual was found. Males did not move far between surveys (average 58.2 ± 24.7 cm) and had small home ranges (0.46 ± 0.20 m²) over the 5-day tracking period. **Implications.** Our study highlights that HDF can be used to track very small vertebrates in structurally complex environments. This method has the potential to fill important knowledge gaps regarding the ecology of small terrestrial breeding amphibians, providing insights that can inform conservation measures and population assessments for vulnerable species.

Keywords: amphibian, conservation, harmonic direction-finder, Microhylids, nursery frogs, oviposition site, site fidelity, telemetry, tracking.

Introduction

Understanding animal movement is key to better understanding a species' behavioural and spatial ecology (Horne *et al.* 2020). The home range of individuals includes the space where daily activities are performed such as access to shelter, food resources, and breeding sites (Odum and Kuenzler 1955; Burt 1943; Gerking 1953). By tracking the movement of an animal, we can obtain information about their habitat preferences, use and requirements, as well as foraging strategies, behaviour, dispersal, homing abilities, and mating system (e.g. Koch and Hero 2007; Ludwig *et al.* 2013; Pašukonis *et al.* 2014; Kingsbury and Robinson 2016; Ayala *et al.* 2019; Garrido-Priego *et al.* 2024). This behavioural and spatial information provides basic ecological data for a species, and can be used to resolve microhabitat requirements (Rowley and Alford 2007), population sizes (Gupta *et al.* 2019), and develop effective conservation measures (Parsons 2016; Fraser *et al.* 2018; Garrido-Priego *et al.* 2024).

Amphibians are the most endangered group of vertebrates, with 40.7% of species under threat (Luedtke *et al.* 2023). Understanding their movement and microhabitat use is key to developing conservation measures for determining suitable areas for breeding and survival (Garrido-Priego *et al.* 2024). Biotelemetry is the most popular method for studying animal movement (McGowan *et al.* 2017). However, this is complicated in many amphibian species due to their small size. While the size and weight of radio transmitters has decreased considerably in the last decade (0.15 g smallest commercially available), they are still too heavy to attach to smaller species (Rowley and Alford 2007). Furthermore, the smaller transmitter constrains battery capacity and, therefore, the device's operational lifespan (Rowley and Alford 2007; Altobelli *et al.* 2022).

Amphibian movement is studied using a variety of methods, often depending on species size and ecological context. The four methods predominantly used in amphibian movement studies are: radio telemetry (e.g. Pašukonis *et al.* 2019; Altobelli *et al.* 2022), harmonic direction finding (HDF, also referred to as harmonic radar, e.g. Moseley and Castleberry 2005; Rowley and Alford 2007; Pašukonis *et al.* 2014, 2019; Borzée *et al.* 2018;), thread-trailing or spooling (Lemckert and Brassil 2000; Schwenke 2016), and the least used method is fluorescent powder (e.g. Rittenhouse *et al.* 2006; Merino-Viteri 2018; reviewed by Altobelli *et al.* 2022). While radio telemetry tags use batteries and constantly transmit a signal, HDF tags modify and 'reflect' a signal emitted from a hand-held transceiver and require no batteries, which makes them light enough for tracking smaller species (Mascanzoni and Wallin 1986; Rowley and Alford 2007; Pašukonis *et al.* 2014; Miller *et al.* 2022; Siderhurst *et al.* 2024), and are much cheaper (US\$3 in materials for HDF versus hundreds of dollars for radio telemetry). However, HDF has relatively lower detection distances (i.e. tens of metres versus hundreds of metres for radio telemetry; Langkilde and Alford 2002; decreasing to 1–2 m in densely vegetated or rocky environments; Sizun 2005; Rowley and Alford 2007) and does not allow for individual identification without extra alteration (Ramírez *et al.* 2017). While spooling can be effective for larger species in more open habitats, it only works for a relatively short amount of time (2–5 days depending on the length of the spool), and the pack or nylon can easily get tangled or caught (Lemckert and Brassil 2000). This technique involves attaching a lightweight spool of thread to the animal to track its movements by manually following the thread. Fluorescent powder can be effective for smaller species, but sufficient powder needs to stick to the animal, and powder dropped in the environment will only remain visible for 1–2 days, and less if it rains (Ramírez *et al.* 2017).

Based on the above information, the HDF method would be the best option for smaller species. Harmonic direction finding has been used in many studies of amphibian movement, but generally for species of moderate to larger size, typically in the range of 2–6 g (Pellet *et al.* 2006; Sapsford *et al.* 2014; Borzée *et al.* 2019), with tags being in the range of 0.07–0.27 g (Altobelli *et al.* 2022). The smallest amphibian tracked to date using HDF is *Allobates femoralis* (1.4–2.3 grams), with tags comprising 3–5% of their body mass (Pašukonis *et al.* 2014), compared to radio telemetry (*Dendrobates tinctorius*, body weight 3.5–4.2 g), with tags comprising 9.5–10% of their body mass (Pašukonis *et al.* 2019). Studies on insects have shown that lighter HDF tags (<1 mg) can be effective for studying movement in very small animals (e.g. Makinson *et al.* 2019; Miller *et al.* 2022; Moore and Siderhurst 2022; Siderhurst *et al.* 2024). Here, we use tags originally designed for insects to effectively track the movement of a very small frog species (<1.5 g weight) while remaining below the recommended threshold of 5–10% of the

amphibian's body weight (Richards *et al.* 1994; Altobelli *et al.* 2022).

Building on advancements in HDF technology for studying small animals, we applied this method to address knowledge gaps in the movement ecology and habitat use of Microhylidae in Australia. The family Microhylidae is represented by two genera: *Cophixalus* (18 species) and *Austrochaperina* (five species) (Zweifel 1985; Hoskin 2004, 2012). This family is increasingly of conservation concern, with five species listed as Critically Endangered and others listed as Endangered or Vulnerable (Gillespie *et al.* 2020; Geyle *et al.* 2021). However, despite their diversity and conservation concerns, there is very little known about their breeding biology and microhabitat use, primarily due to their typically restricted distributions, small size and cryptic nature. Using HDF, we aimed to determine the scale of movements, home range size, nesting sites, and microhabitat use of male robust whistling frogs (*Austrochaperina robusta*) during their breeding season.

Materials and methods

Study area and species

Cophixalus and *Austrochaperina* are terrestrial breeders with direct development (i.e. embryos develop to metamorphosis within the jelly capsules) and perform paternal care (Hoskin 2004). In this study, we use the common species *Austrochaperina robusta* (robust whistling frog) as a model for other microhylids of similar ecology. *Austrochaperina robusta* is small-sized (22–32 mm snout-vent length) and restricted to mid-elevation (~600–1000 m.a.s.l.) and upland rainforest of the Wet Tropics region of northeastern Queensland, Australia, where it has a cryptic life history among leaf litter and under logs and rocks (Hoskin and Hero 2008). Males call at night from the leaf litter, close to surface objects such as logs and roots and are mostly inactive during the day (Groffen *et al.* 2024). The clutch (9–15 eggs) is laid in leaf litter or under a log or rock and is attended by an adult male (Hoskin 2004; Anstis *et al.* 2011). *Austrochaperina robusta* can be found in high density, but because of their small size and cryptic life history, little is known of their home range, movement behaviour, and nesting sites. In this study, home range is defined as the spatial area used by the study species during a 5-day tracking period during the breeding season.

Tracking system and tag attachment

The harmonic direction-finding (HDF) system consists of a passive reflector/transponder diode 'tag' and an active directional transceiver, in this case, a RECCO hand-held transceiver (RECCO R9 Handheld Detector, www.recco.com) (Mascanzoni and Wallin 1986). The tags generally consist of one or, most commonly (this study), two wires attached to a Schottky diode. Harmonic tags do not use batteries. Instead,

they modify (double) the signal emitted from the transceiver (~900 MHz in this case), which can then be used to triangulate the location of the animal (Leskovar and Sinsch 2005; Rowley and Alford 2007).

The most widely used method for tracking anurans via HDF involves fitting tags on top of a silicone tube, measuring 1.5 mm in diameter, to create a harness (Fig. 1a; reviewed by Altobelli *et al.* 2022). Due to the small size of our study species, we used 0.5 mm diameter medical-grade silicone tubing. We placed the harness in front of the frog's hindlegs, at the narrowest part of the body, to prevent the harness from sliding forward up the body or backward off the hindlegs (Fig. 1a; Bartelt and Peterson 2000; Pašukonis *et al.* 2014; Fischer *et al.* 2020). The harness was fastened via a cotton thread fitted through the tube (Natural cotton C Ne #50 Gutermann), which was tied using a double reef knot. The cotton is expected to break and release the harness after approximately two to three weeks (Beck *et al.* 2017), in case an individual is unable to be recaptured. Each harness had a harmonic radar tag attached with super glue (Loctite Super Glue). Two sizes of tags were tested, both fabricated from a Schottky diode with two super elastic nitinol wire antennas attached to form a dipole (for more details see Miller *et al.* 2022; Siderhurst *et al.* 2024). The smaller tags were made with a small diode and two 4 cm lengths of 0.025 mm diameter nitinol wire (~1 mg total mass; Miller *et al.* 2022), while the larger tags were made with a larger diode and two 8 cm lengths of 0.076 mm diameter nitinol wire (~15 mg total mass; Siderhurst *et al.* 2024). The 'hair like' antennas were oriented transversely on the frog (protruding to the left and right) and could be bent in any direction so as not to obstruct the frog's movement (Fig. 1a).

Locating frogs

Surveys for calling males were conducted in their breeding season between 8–15 January 2024, after sunset (19:00–23:30 h), along a 1.4 km existing trail in the rainforest

uplands of the Paluma Range ('H-Track'; 19.0107°S, 146.2055°E), north Queensland, Australia. Once a calling male was found, it was caught and placed in a Ziplock bag, with moist leaf litter added to minimise stress. Snout-vent length (SVL) was measured to the nearest 0.01 mm with callipers and the weight was taken to the nearest 0.01 g using a 10 g Pesola® spring scale. A small or large tag was fitted, as outlined above. Flagging tape with individual ID, date, and survey number was used to mark the capture location, and GPS coordinates were recorded. Handling time and tag size were recorded, and the captured individual was placed back at the exact capture location and covered with a leaf. Microhabitat notes were recorded for each capture location. The following environmental measurements were recorded: ambient temperature, humidity (%), precipitation (Yes/No), and number of other male *A. robusta* calling within 5 metres.

Each tagged individual was subsequently located a minimum of two times per 24-h period: once during daytime (10:30–19:00 h) and once during the night (20:00–00:00 h). Once we were in the vicinity (i.e. within 2 meters) of the last known location of a tagged frog, the RECCO hand-held transceiver was turned on and a timer was started as the start time for searching. The timer was stopped when we had a visual of the frog with harness or a detached harness. Once the frog was found, location, microhabitat notes (same as original capture, see paragraph above), search time and time of day were recorded. We stopped searching after 15 min (900 s) if the frog had not been located. If the tagged individual had moved from the previously recorded location, flagging tape with individual number, date, and survey number was placed at the new location. We recorded the distance and GPS bearing to previous capture location, and distance to closest object (log, rock, root or tree). If the transceiver suggested the same location as the previous survey (i.e. within 5 cm), we did not uncover the frog (to minimise disturbance), but if this repeated at the next survey, we searched for the frog to ensure it had not lost the harness. After 48 h, each tagged individual was captured and

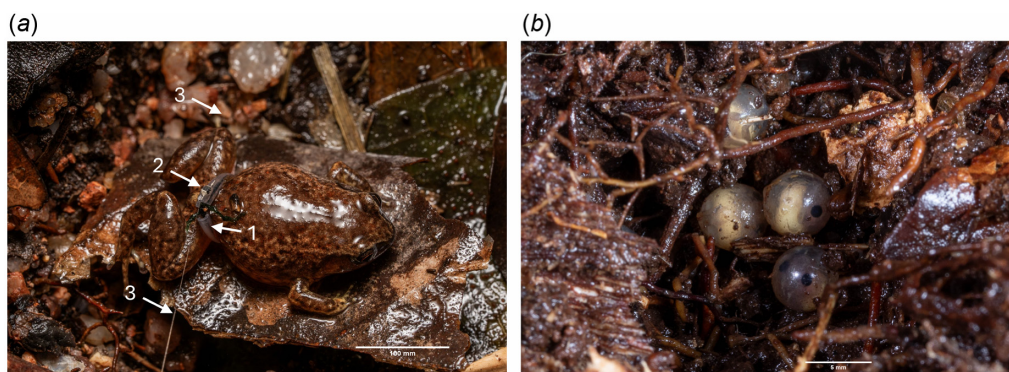


Fig. 1. (a) Adult male *Austrochaperina robusta* with harness (1), which includes the Schottky diode (2) and nitinol antennas (3) (Photo by J. Bartholomew). (b) Egg clutch of one of the tracked individuals (Photo by S. Macor).

checked for potential injuries from the harness and tag. These were assessed by looking for visible surface wounds or abrasions around the harness area. The frog was then released at the exact point of capture. After 5 days, each tagged individual was recaptured and the harness removed. Following harness removal, each individual was checked again for potential injuries from the harness/tag, and handling time was once again recorded. Only individuals with three or more location records (regardless of whether each record involved actual movement) were used for calculations of movement distances and minimal home range size.

Home range estimation

At the end of the tracking period, photographs were taken from approximately 1.5 m looking down onto the forest floor, with all flagging tape markers of locations visible, to document the frog's home range. A minimum convex polygon (MCP) method (Mohr 1947) was used to estimate home range by importing the images into ImageJ (Schindelin *et al.* 2012) and using the polygon measure function. Other studies also calculate kernel density estimates to complement the MCP method (e.g. Garrido-Priego *et al.* 2024). But for our home ranges, the precision of locations and location numbers were too small to use this or similar methods.

Statistical analyses

All analyses were conducted in R version 4.3.2. We used the lme4 package (Bates *et al.* 2015) to run all models and ggplot2 (Wickham 2016) to construct figures. To examine if tag size (fixed effect) influenced the search time until found (response variable), and distance travelled (response variable), we used a linear mixed model (gaussian distribution) and a generalised linear mixed model (gaussian distribution), respectively. When a tag was not found, a search time of 900 s was recorded in the dataset. A linear mixed model was used to examine if there was a difference between search time until located between daytime and nighttime surveys. The models included frog ID as a random effect to account for the repeated measures per individual.

Results

Twenty-two adult male *A. robusta* were tagged between 8–20 January 2024, of which 11 individuals (50%) lost their harnesses within the first 15 h. The average weight of the tagged frogs was 1.27 ± 0.20 g, and the average length was 22.45 ± 0.91 mm (SVL). One individual lost the harness after 3 days and another after 4 days, resulting in six and eight locations, respectively. The remaining nine frogs that were tracked for the full 5-day tracking period had locations recorded at least twice a day, resulting in a total of 10–13 locations per frog (Table 1). All frogs were hidden underneath

the leaf litter (i.e. between the leaf litter and soil) or in small holes in the ground during daytime. A general pattern observed was that frogs often remained hidden under the leaf litter, in holes, or burrows during the day and moved to the upper layers of the leaf litter at night. On average, frogs were just as likely to be recorded at a different location between checks (54%, range 33–83%) as the same location. Average ambient temperature during the tracking period was $22.2 \pm 4.8^\circ\text{C}$, humidity was always above 96%, and it rained to some degree every day (average daily precipitation was 15.3 ± 11.8 mm).

Tag size

Average frog weight ($\pm$ s.d.) was 1.27 ± 0.20 g and harness/tag weights were 0.023 ± 0.005 g ($n = 7$) for the smaller tags (tag average 1.80% of body weight, range 1.5–2.1%) and 0.033 ± 0.004 g ($n = 4$) for the larger tag (tag average 2.58% of body weight, range 2.1–2.9%) (Table 1). In all cases, the combined weight of the harness and tag was under the standard threshold of 5–10% of the amphibian's body weight recommended in the literature (Richards *et al.* 1994; Altobelli *et al.* 2022). Tagged individuals could not be located in seven of the 116 surveys (9.7% of location checks). Individuals with the smaller tags took on average 258 ± 106 s to be located and were unable to be located on five occasions (6.9%; all during daytime searches), while individuals with the larger tags took on average 233 ± 87 s to be located and were unable to be located on only two occasions (4.5% of location checks, once during daytime and once during nighttime). Although these numbers fit the expectation that larger tags are more readily found, there was no overall difference in search time between tag sizes ($R^2 = 0.21$, $\beta = 23.53$, $P = 0.76$, Supplementary Fig. S1A). There was also no significant difference between the time it took to locate a frog and the time of day ($R^2 = 0.19$, $\beta = -17.88$, $P = 0.68$, Fig. S1C).

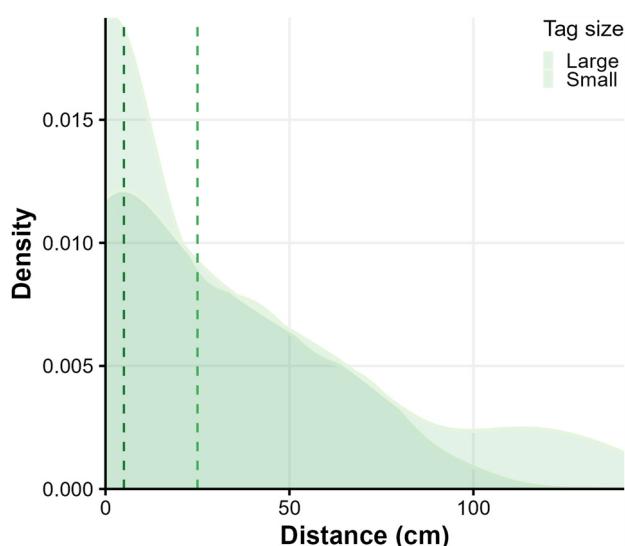
Handling time for the original capture was an average ($\pm$ s.d.) of 13.1 ± 5.6 min and 7.2 ± 4.0 min for removal of the harness at the end of the study. During the 48-h check, there were no signs of injuries, however, after the 5-day period one individual had two small lesions where the harness had been.

Home range and distance travelled

The average distance moved between two consecutive surveys was 58.2 ± 24.7 cm (mean $\pm$ s.d.; $n = 62$ movements, Fig. 2 and Fig. S1). The longest movement from the previous check was 141 cm, and the furthest distance moved from the original capture site was 173 cm (Table 1). The average home range across the 11 frogs was 0.46 ± 0.20 m² (range 0.19–0.76 m², Figs 2, 3). One frog had a nest with four eggs in terrestrial development stage 10–11 (Anstis 2013; Fig. 1b). During night surveys, tagged males had other *A. robusta* males (1–3 males) calling within 5 metres 57.4%

Table 1. Size of frogs and tags, average movement, distance travelled, and home range of the eleven tagged male *Austrochaperina robusta*.

ID	# check	Capture date	Size (mm)	Weight (g)	Tag size	% of body weight	Average search time (s) $\pm$ s.e.	Times moved	Average movement (cm) $\pm$ s.e.	Cumulative distance moved (cm)	Longest distance between surveys (cm)	Longest distance from capture (cm)	Home range (m ²)	Net displacement (cm)
A	10	10/01/2024	21.2	1.15	Large	2.9	340 $\pm$ 35	7	38.6 $\pm$ 5.8	272	63	103	0.62	103
B	13 ^A	10/01/2024	22.6	1.25	Large	2.6	287 $\pm$ 81	5	47.8 $\pm$ 15	191	70	90	0.32	69
C	8 ^A	09/01/2024	21.6	1.5	Small	1.5	268 $\pm$ 158	3	110 $\pm$ 23	330	133	163	0.45	64
D	12 ^B	12/01/2024	21.1	1.4	Small	1.6	477 $\pm$ 89	10	40 $\pm$ 6.6	400	75	92	0.54	45
E	12	12/01/2024	21.5	0.84	Small	2.7	270 $\pm$ 66	8	51.4 $\pm$ 14.3	411	141	169	0.65	44
F	12	12/01/2024	24.1	1.4	Small	1.6	184 $\pm$ 55	4	93.8 $\pm$ 13.7	375	123	173	0.66	173
G	11	15/01/2024	23.1	1.4	Small	1.6	84 $\pm$ 15	6	48 $\pm$ 7.6	288	68	134	0.27	106
H	11 ^B	15/01/2024	21.3	1.55	Small	1.5	210 $\pm$ 103	4	51.5 $\pm$ 20.9	206	114	114	0.19	98
I	10	10/01/2024	22.9	1.6	Large	2.1	188 $\pm$ 54	6	49.5 $\pm$ 11.5	297	94	152	0.76	92
J	6 ^B	12/01/2024	21.2	1.1	Small	2.1	316 $\pm$ 81	5	77.6 $\pm$ 15.8	388	107	29	0.28	47
K	11	08/01/2024	22	1.25	Large	2.6	118 $\pm$ 33	4	32.4 $\pm$ 6.7	129.6	71	106	0.09	80

^ACould not be found twice.^BCould not be found once.**Fig. 2.** Density plot showing the distribution of movement distances between tracking locations, and the relationship between tag size ('small' tag = dark green; 'large tag' = light green) and movements for the eleven tracked males *Austrochaperina robusta*. Dashed lines are medians. Movement distances are for all frogs (n small tags = 7, n large tags = 4).

of the time. On five occasions, a non-tagged individual was located within 50 cm of a tagged individual: three non-calling adults (sex unknown, 5 cm, 12.5 cm and 23 cm away), one calling male (46 cm), and one metamorph (9 cm). There was no significant difference between tag size and distance travelled ($R^2 = 0.02$, $\beta = 11$, $P = 0.17$, Fig. S1). Out of 11 frogs, three individuals (27.3%) did not show an increase in their minimum convex polygon (MCP, minimal home range size) after the first three locations were

recorded; others often moved away and then returned close to the original capture site but expanded their MCP (Fig. S2).

Discussion

In this study, we used an ultra-light tag and harness (0.023–0.033 g) to study the movements, home range, habitat use, and nesting sites of a small (22.45 ± 0.91 mm) and very light (1.27 ± 0.20 g) terrestrial breeding frog species, *Austrochaperina robusta*. Our primary ecological findings are (1) frogs moved remarkably small distances and had uniformly small home ranges, (2) frogs are on or near the surface at night and deeper in the leaf litter/soil during the day, and (3) the tracking can lead to the location of egg clutches. In terms of technique assessment, both the 'small' and 'large' harness/tag setups were highly effective for this species, and we saw no significant ethical issues for using the technique with frogs. Furthermore, to the best of our knowledge, these are the lightest harness/tag setups used in amphibian tracking studies to date, being over 50% lighter than previous systems (previous lightest harness/tag was 0.07 g; Altobelli *et al.* 2022).

Despite the minimal weight of our harness/tag setup, half of the tagged individuals lost their harness in the first 15 h. Like many other Anuran species, when *A. robusta* is under threat, they inflate themselves with air to look larger. When captured, *A. robusta* showed this defensive behaviour, resulting in some harnesses being attached too loosely. Additionally, we observed that they often pushed themselves through small spaces in the leaf litter and soil, potentially dislodging the harness. These are the suspected main causes of harness loss,

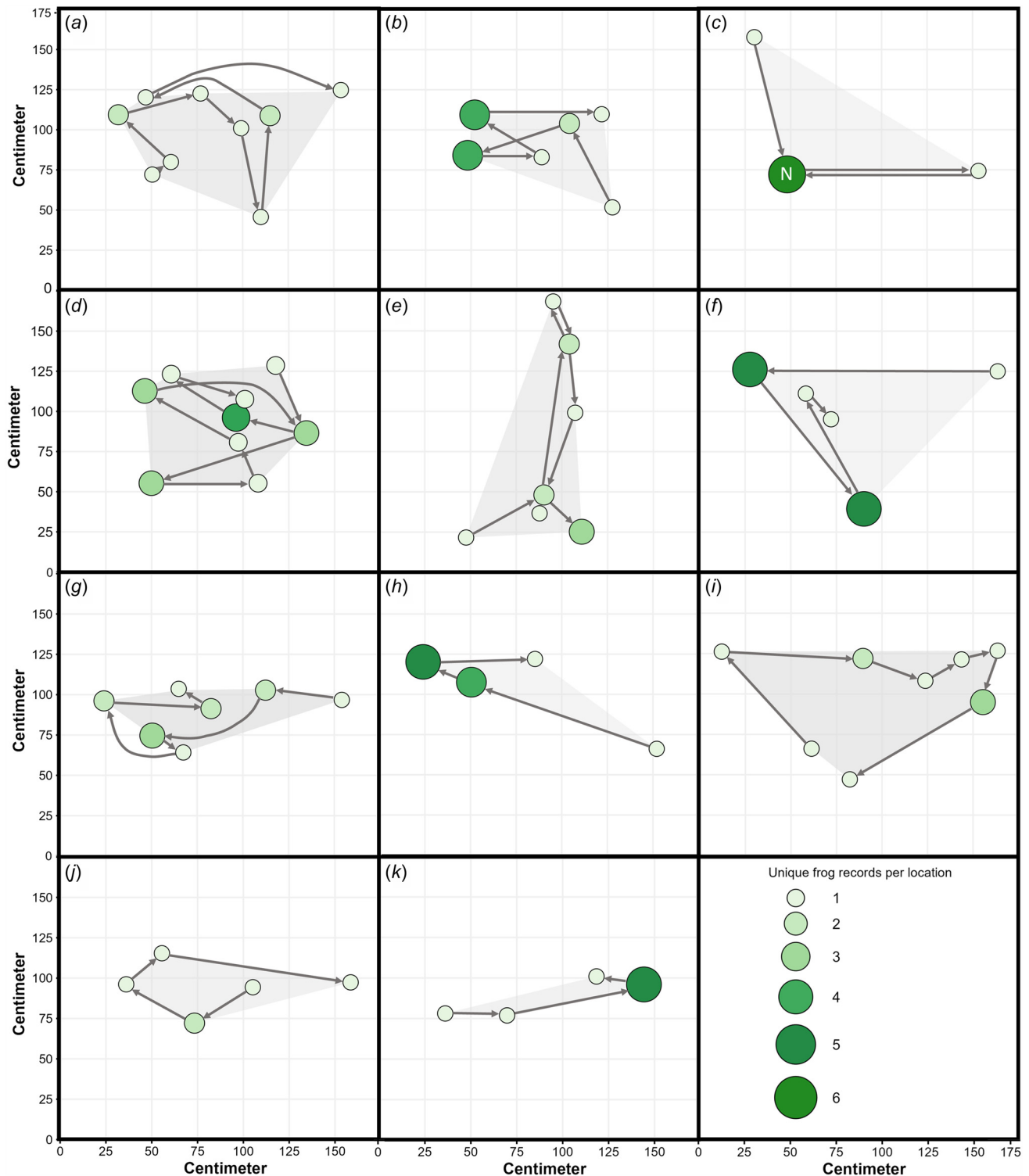


Fig. 3. Movements and home range visualisation of 11 tagged *A. robusta* individuals in a 5-day period. The size and colour of the bubble indicates the number of unique frog records per location. The light grey polygons show the minimum estimated home ranges. The 'N' in panel (c) indicates the location of the nest. The letters of each panel relate to the Frog ID column in Table 1.

especially at the start of the study (8 of the first 10 frogs lost their harness). Harnesses were subsequently tied tighter, which improved retention of the harnesses and caused little

adverse effect to the frogs, aside from possibly two small lesions on one individual at the end of the 5-day tracking period.

There was no significant difference between tag size and search time, likely due to the small home range of the study species and the light weight of both the small and large tags. Furthermore, the small sample size might also influence this. However, the smaller tags were more often unlocated when the frogs were deeper in the leaf litter. Therefore, we recommend using the larger tag size for species with a larger home range or those that are more fossorial. The smaller tag size is suitable for smaller species to stay under the recommended 5% of their body weight, have a small home range, or are more epigeal.

Home range size and body size have been shown to be positively correlated in a number of frog species (Duellman and Trueb 1986). Other similarly small frogs tracked to date also have small home range sizes, but our home range size estimates for *A. robusta* ($0.46 \pm 0.20 \text{ m}^2$, range $0.19\text{--}0.76 \text{ m}^2$) are small even compared to these. For example, *Rhinoderma darwinii* (22–31 mm SVL) have an average home range of $1.82 \pm 0.54 \text{ m}^2$ (range $0.1\text{--}16 \text{ m}^2$; Valenzuela-Sánchez *et al.* 2014), *Hylodes dactylocinus* (24–27 mm SVL) home ranges average $2.2 \pm 2.1 \text{ m}^2$ ($0.12\text{--}13.12 \text{ m}^2$; Narvaes and Rodrigues 2005), and *Phyllobates vittatus* (24 mm SVL) average 55.7 m^2 ($36.95\text{--}67.64 \text{ m}^2$; Garrido-Priego *et al.* 2024). We tracked the individuals for a maximum of 5 days, whereas some of these studies mentioned above tracked frogs for longer, which may generate larger home range estimates. Additionally, we only tracked in the breeding season, and home ranges could be larger during the non-breeding season (Duellman and Trueb 1986; Wells 2007). While some individuals kept increasing their minimum convex polygon (MCP), the later direction was often towards the original capture site, showing high site fidelity. This might reflect only a snapshot of the individual's spatial behaviour during this specific period and may not encompass their full annual or lifetime range. However, based on the strong site fidelity and extremely sedentary behaviour of the species in this study and others (Groffen and Hoskin 2024, unpubl. data), we do not expect that the home range will increase drastically.

The ability to follow individual frogs as they move in their environment allows observations of much more granular spatial/temporal observations of life history and behaviours. Individuals may defend their territory to secure limited resources such as food, calling sites, mates, eggs, and shelters (Duellman and Trueb 1986; Grant 1993; Wollenberg and Harvey 2010). Many terrestrial Anuran species with parental care show territorial behaviour to protect certain habitat requirements, resources, and eggs (Garrido-Priego *et al.* 2024). While locating tagged individuals, we sometimes found another adult *A. robusta* in very close proximity, and in 57.4% of the night checks a calling male was within 5 m of a tagged individual. These results suggest that *A. robusta* has very small territories and is tolerant of other individuals in close proximity. Adult male *A. robusta* were found deep under the leaf litter or in the soil during the daytime and in the top layer of the leaf litter after dark. This fits expectations,

with the frogs sheltering in moist, cool, hidden conditions during the day and being on the surface during nocturnal activity (calling for females (Groffen *et al.* 2024), moving, and presumably foraging). *Austrochaperina robusta* does not have a clumped breeding habitat (moist leaf litter) and is a generalist feeder of small invertebrates (Williams *et al.* 2006), and these evenly distributed and abundant resources may limit territorial behaviour.

These behavioural insights raise further questions about the species' reproductive strategies and nest-site fidelity. While *A. robusta* are abundant in their localised range, little is known of their ecology and breeding biology due to their small size, cryptic habits, and difficulty finding nests. In this study, one of the tagged individuals was found on a nest in a small depression (4 cm deep) in the soil under leaf litter and a small log. There were only four eggs (average clutch size is 12; Hoskin 2004; Anstis *et al.* 2011). This male was caught the night before calling 64 cm away from the nest. While the harness was lost after 3 days (133 cm away from the nest), the data showed that the male often spent time at the nest (Fig. 3c).

Using ultra-light harness and HDF – tag systems, we successfully tracked the fine-scale movements and habitat use of the small terrestrial frog *Austrochaperina robusta*. The technique proved effective and minimally invasive. Ecologically, we found that *A. robusta* has extremely small home ranges, strong site fidelity during the breeding season, and shows tolerance to conspecifics at close distances, likely due to abundant, evenly distributed resources. Tracking also enabled rare observations of nesting location.

Supplementary material

Supplementary material is available [online](#).

References

- Altobelli JT, Dickinson KJM, Godfrey SS, Bishop PJ (2022) Methods in amphibian biotelemetry: two decades in review. *Austral Ecology* **47**, 1382–1395. doi:10.1111/aec.13227
- Anstis M (2013) Genus *Austrochaperina* Fry, 1912. In 'Tadpoles and frog of Australia'. pp. 775–784. (New Holland Publishers Pty Ltd)
- Anstis M, Parker F, Hawkes T, Morris I, Richards SJ (2011) Direct development in some Australopapuan microhylid frogs of the genera *Austrochaperina*, *Cophixalus* and *Oreophryne* (Anura: Microhylidae) from northern Australia and Papua New Guinea. *Zootaxa* **3052**, 1–50. doi:10.11646/zootaxa.3052.1.1
- Ayala C, Ramos AG, Merlo Á, Zambrano L (2019) Microhabitat selection of axolotls, *Ambystoma mexicanum*, in artificial and natural aquatic systems. *Hydrobiologia* **828**, 11–20. doi:10.1007/s10750-018-3792-8
- Bartelt PE, Peterson CR (2000) A description and evaluation of a plastic belt for attaching radio transmitters to western toads (*Bufo boreas*). *Northwestern Naturalist* **81**, 122–128. doi:10.2307/3536823
- Bates D, Mächler M, Bolker B, Walker S (2015) Fitting linear mixed-effects models using lme4. *Journal of Statistical Software* **67**, 1–48. doi:10.18637/jss.v067.i01
- Beck KB, Loretto MC, Ringler M, Hödl W, Pašukonis A (2017) Relying on known or exploring for new? movement patterns and reproductive resource use in a tadpole-transporting frog. *PeerJ* **2017**, 1–24. doi:10.7717/peerj.3745

- Borzée A, Kim YI, Kim K, Yikweon J (2018) Methodological development for harmonic direction finder tracking in salamanders. *Herpetological Conservation and Biology* 13, 473–478.
- Borzée A, Choi Y, Kim YE, Jablonski PG, Jang Y (2019) Interspecific variation in seasonal migration and brumation behaviour in two closely related species of treefrogs. *Frontiers in Ecology and Evolution* 7, 55. doi:10.3389/fevo.2019.00055
- Burt WH (1943) Territoriality and home range concepts as applied to mammals. *Journal of Mammalogy* 24, 346–352. doi:10.2307/1374834
- Duellman WE, Trueb L (1986) 'Biology of amphibians.' (The Johns Hopkins University Press, USA)
- Fischer MT, Ringler M, Ringler E, Pašukonis A (2020) Reproductive behavior drives female space use in a sedentary Neotropical frog. *PeerJ*, 8, e8920. doi:10.7717/peerj.8920
- Fraser KC, Davies KTA, Davy CM, Ford AT, Flockhart DTT, Martins EG (2018) Tracking the conservation promise of movement ecology. *Frontiers in Ecology and Evolution* 6, 150. doi:10.3389/fevo.2018.00150
- Garrido-Priego M, Monge-Velázquez M, Whitworth A, Gomez-Mestre I (2024) Home range and notes about social interactions in the poison frog *Phyllobates vittatus* (Anura: Dendrobatidae). *Evolutionary Ecology*. 38, 193–204. doi:10.1007/s10682-023-10284-y
- Gerking SD (1953) Evidence for the concepts of home range and territory in stream fishes. *Ecology* 34, 347–365. doi:10.2307/1930901
- Geyle HM, Hoskin CJ, Bower DS, Catullo R, Clulow S, Driessen M, Daniels K, Garnett ST, Gilbert D, Heard GW, Hero JM, Hines HB, Hoffmann EP, Hollis G, Hunter DA, Lemckert F, Mahony M, Marantelli G, McDonald KR, Mitchell NJ, Newell D, Roberts JD, Scheele BC, Scroggie M, Vanderduys E, Wassens S, West M, Woinarski JCZ, Gillespie GR (2021) Red hot frogs: Identifying the Australian frogs most at risk of extinction. *Pacific Conservation Biology* 28(3), 211–223. doi:10.1071/PC21019
- Gillespie GR, Roberts JD, Hunter D, Hoskin CJ, Alford RA, Heard GW, Hines H, Lemckert F, Newell D, Scheele BC (2020) Status and priority conservation actions for Australian frog species. *Biological Conservation* 247, 108543. doi:10.1016/j.biocon.2020.108543
- Grant JWA (1993) Whether or not to defend? The influence of resource distribution. *Marine Behaviour and Physiology* 23, 137–153. doi:10.1080/10236249309378862
- Groffen J, Rush ER, Hoskin CJ (2024) Calling locations and courtship calls of the frogs *Austrochaperina robusta* Fry, 1912 and *Pseudophryne covacevichae* Ingram & Corben, 1994 in northern Australia. *Herpetology Notes* 17, 315–321.
- Gupta A, Dilkina B, Morin DJ, Fuller AK, Royle JA, Sutherland C, Gomes CP (2019) Reserve design to optimize functional connectivity and animal density. *Conservation Biology* 33, 1023–1034. doi:10.1111/cobi.13369
- Horne JS, Fieberg J, Börger L, Rachlow JL, Calabrese JM, Fleming CH (2020) Animal home ranges: concepts, uses, and estimation. In 'Population ecology: in practice'. (Eds D Murray, B Sandercock) pp. 315–332. (Wiley Blackwell: New York)
- Hoskin CJ (2004) Australian microhylid frogs (*Cophixalus* and *Austrochaperina*): phylogeny, taxonomy, calls, distributions and breeding biology. *Australian Journal of Zoology* 52, 237–269. doi:10.1071/ZO03056
- Hoskin CJ (2012) Two new frog species (Microhylidae: Cophixalus) from the Australian Wet Tropics region, and redescription of *Cophixalus ornatus*. *Zootaxa* 3271, 1–16. doi:10.11646/zootaxa.3271.1.1
- Hoskin CJ, Hero J-M (2008) 'Rainforest frogs of the wet tropics.' (Griffith University: Gold Coast, Qld, Australia)
- Kingsbury BA, Robinson NJ (2016) Movement patterns and telemetry. In 'Reptile ecology and conservation: a handbook of techniques.' (Ed. C Kenneth Dodd) p. 110. (Oxford University Press)
- Koch AJ, Hero JM (2007) The relationship between environmental conditions and activity of the giant barred frog (*Mixophyes iteratus*) on the Coomera River, south-east Queensland. *Australian Journal of Zoology* 55, 89–95. doi:10.1071/ZO06017
- Langkilde T, Alford RA (2002) The tail wags the frog: harmonic radar transponders affect movement behavior in *Litoria lesueuri*. *Journal of Herpetology* 36, 711–715. doi:10.1670/0022-1511(2002)036[0711:TTWTFH]2.0.CO;2
- Lemckert F, Brassill T (2000) Movements and habitat use of the endangered giant barred river frog (*Mixophyes iteratus*) and the implications for its conservation in timber production forests. *Biological Conservation* 96, 177–184. doi:10.1016/S0006-3207(00)00066-5
- Leskovar C, Sinsch U (2005) Harmonic direction finding: a novel tool to monitor the dispersal of small-sized anurans. *Herpetological Journal* 15, 173–180.
- Ludwig G, Sinsch U, Pelster B (2013) Migratory behaviour during autumn and hibernation site selection in common frogs (*Rana temporaria*) at high altitude. *The Herpetological Journal* 23, 121–124.
- Luedtke JA, Chanson J, Neam K, Hobin L, Maciel AO, Catenazzi A, Borzée A, Hamidy A, Aowphol A, Jean A, Sosa-Bartuano Á, Fong GA, de Silva A, Fouquet A, Angulo A, Kidov AA, Muñoz Saravia A, Diesmos AC, Tominaga A, Shrestha B, Gratwicke B, Tjaturadi B, Martínez Rivera CC, Vásquez Almazán CR, Señaris C, Chandramouli SR, Striissmann C, Cortez Fernández CF, Azat C, Hoskin CJ, Hilton-Taylor C, Whyte DL, Gower DJ, Olson DH, Cisneros-Heredia DF, Santana DJ, Nagombi E, Najafi-Majd E, Quah ESH, Bolaños F, Xie F, Brusquetti F, Álvarez FS, Andreone F, Glaw F, Castañeda FE, Kraus F, Parra-Olea G, Chaves G, Medina-Rangel GF, González-Durán G, Ortega-Andrade HM, Machado IF, Das I, Dias IR, Urbina-Cardona JN, Crnobrnja-Isailović J, Yang JH, Jianping J, Wangyal JT, Rowley JJJ, Measey J, Vasudevan K, Chan KO, Gururaja KV, Ovaska K, Warr LC, Canseco-Márquez L, Toledo LF, Díaz LM, Khan MMH, Meegaskumbura M, Acevedo ME, Napoli MF, Ponce MA, Vaira M, Lampo M, Yáñez-Muñoz MH, Scherz MD, Rödel MO, Matsui M, Fildor M, Kusri MD, Ahmed MF, Rais M, Kouamé NGG, García N, Gonwouo NL, Burrows PA, Imbun PY, Wagner P, Kok PJR, Joglar RL, Auguste RJ, Brandão RA, Ibáñez R, von May R, Hedges SB, Biju SD, Ganesh RJ, Wren S, Das S, Flechas SV, Ashpole SL, Robleto-Hernández SJ, Loader SP, Incháustegui SJ, Garg S, Phimmachak S, Richards SJ, Slimani T, Osborne-Naikatini T, Abreu-Jardim TPF, Condez TH, De Carvalho TR, Cutajar TP, Pierson TW, Nguyen TQ, Kaya U, Yuan Z, Long B, Langhammer P, Stuart SN (2023) Ongoing declines for the world's amphibians in the face of emerging threats. *Nature* 622, 308–314. doi:10.1038/s41586-023-06578-4
- Makinson JC, Woodgate JL, Reynolds A, Capaldi EA, Perry CJ, Chittka L (2019) Harmonic radar tracking reveals random dispersal pattern of bumblebee (*Bombus terrestris*) queens after hibernation. *Scientific Reports* 9, 1–11. doi:10.1038/s41598-019-40355-6
- Mascanzoni D, Wallin H (1986) The harmonic radar: a new method of tracing insects in the field. *Ecological Entomology* 11, 387–390. doi:10.1111/j.1365-2311.1986.tb00317.x
- McGowan J, Beger M, Lewison RL, Harcourt R, Campbell H, Priest M, Dwyer RG, Lin HY, Lentini P, Dudgeon C, McMahon C, Watts M, Possingham HP (2017) Integrating research using animal-borne telemetry with the needs of conservation management. *Journal of Applied Ecology* 54, 423–429. doi:10.1111/1365-2664.12755
- Merino-Viteri AR (2018) The vulnerability of microhylid frogs, *Cophixalus* spp., to climate change in the Australian Wet Tropics. PhD thesis. James Cook University. Available at <http://doi.org/10.4225/28/5b0c8d84e69b2>
- Miller ND, Yoder TJ, Manoukis NC, Carvalho LAFN, Siderhurst MS (2022) Harmonic radar tracking of individual melon flies, *Zeugodacus cucurbitae*, in Hawaii: determining movement parameters in cage and field settings. *PLoS ONE* 17, e0276987. doi:10.1371/journal.pone.0276987
- Mohr CO (1947) Table of equivalent populations of North American small mammals. *American Midland Naturalist* 37, 223–249.
- Moore A, Siderhurst M (2022) Proposal for detecting coconut rhinoceros beetle breeding sites using harmonic radar. *Research Ideas and Outcomes* 8, e86422. doi:10.3897/rio.8.e86422
- Moseley KR, Castleberry SB (2005) Assessment of subcutaneously implanted reflector tags for relocating mole salamanders (*Ambystoma talpoideum*). *Georgia Journal of Science* 63, 91–96.
- Narvaes P, Rodrigues MT (2005) Visual communication, reproductive behavior, and home range of *Hylodes dactylocinus* (Anura, Leptodactylidae). *Phyllomedusa* 4, 147–158. doi:10.11606/issn.2316-9079.v4i2p147-158
- Odum EP, Kuenzler EJ (1955) Measurement of territory and home range size in birds. *Ornithology* 72, 128–137. doi:10.2307/4081419
- Parsons ECM (2016) Why IUCN should replace "data deficient" conservation status with a precautionary "assume threatened" status—A cetacean case study. *Frontiers in Marine Science* 3, 193. doi:10.3389/fmars.2016.00193

- Pašukonis A, Loretto MC, Landler L, Ringler M, Hödl W (2014) Homing trajectories and initial orientation in a Neotropical territorial frog, *Allobates femoralis* (Dendrobatidae). *Frontiers in Zoology* 11, 29. doi:10.1186/1742-9994-11-29
- Pašukonis A, Loretto MC, Rojas B (2019) How far do tadpoles travel in the rainforest? Parent-assisted dispersal in poison frogs. *Evolutionary Ecology* 33, 613–623. doi:10.1007/s10682-019-09994-z
- Pellet J, Rechsteiner L, Skriversvik AK, Zürcher JF, Perrin N (2006) Use of the harmonic direction finder to study the terrestrial habitats of the European tree frog (*Hyla arborea*). *Amphibia Reptilia* 27, 138–142. doi:10.1163/156853806776052173
- Ramírez PA, Bell BD, Germano JM, Bishop PJ, Nelson NJ (2017) Tracking a small cryptic amphibian with fluorescent powders. *New Zealand Journal of Ecology* 41, 134–138. doi:10.20417/nzjecol.41.2
- Richards SJ, Sinsch U, Alford RA (1994) Radio tracking. In 'Measuring and monitoring biological diversity: standard methods for amphibians'. (Eds WR Heyer, MA Donnelly, RW McDiarmid, L-AC Hayek, MS Foster) pp. 155–158. (The Smithsonian Institution: Washington)
- Rittenhouse TAG, Altnether TT, Semlitsch RD (2006) Fluorescent powder pigments as a harmless tracking method for ambystomatids and ranids. *Herpetological Review* 37, 188–191.
- Rowley JJJ, Alford RA (2007) Techniques for tracking amphibians: the effects of tag attachment, and harmonic direction finding versus radio telemetry. *Amphibia Reptilia* 28, 367–376. doi:10.1163/156853807781374755
- Sapsford SJ, Roznik EA, Alford RA, Schwarzkopf L (2014) Visible implant elastomer marking does not affect short-term movements or survival rates of the treefrog *Litoria rheocola*. *Herpetologica* 70, 23–33. doi:10.1655/HERPETOLOGICA-D-13-0004
- Schindelin J, Arganda-Carreras I, Frise E, Kaynig V, Longair M, Pietzsch T, Preibisch S, Rueden C, Saalfeld S, Schmid B, Tinevez J-Y, White DJ, Hartenstein V, Eliceiri K, Tomancak P, Cardona A (2012) Fiji: an open-source platform for biological-image analysis. *Nature Methods* 9, 676–682. doi:10.1038/nmeth.2019
- Schwenke AC (2016) Riparian vegetation condition influences movement and microhabitat use by *Mixophyes fasciolatus* in South East Queensland. Thesis (Masters by Research). Queensland University of Technology.
- Siderhurst MS, Murman KM, Kaye KT, Wallace MS, Cooperband MF (2024) Radio telemetry and harmonic radar tracking of the spotted lanternfly, *Lycorma delicatula* (White) (Hemiptera: Fulgoridae). *Insects* 15, 17. doi:10.3390/insects15010017
- Sizun H (2005) 'Radio wave propagation for telecommunication applications.' (Springer: Heidelberg)
- Valenzuela-Sánchez A, Harding G, Cunningham AA, Chirgwin C, Soto-Azat C (2014) Home range and social analyses in a mouth brooding frog: testing the coexistence of paternal care and male territoriality. *Journal of Zoology* 294, 215–223. doi:10.1111/jzo.12165
- Wells KD (2007) 'The ecology and behavior of amphibians.' (University of Chicago Press: Chicago)
- Wickham H (2016) 'ggplot2: Elegant Graphics for Data Analysis'. (Springer-Verlag: New York) Available at <https://ggplot2.tidyverse.org>
- Williams YM, Williams SE, Alford RA, Waycott M, Johnson CN (2006) Niche breadth and geographical range: ecological compensation for geographical rarity in rainforest frogs. *Biology Letters* 2, 532–535. doi:10.1098/rsbl.2006.0541
- Wollenberg KC, Harvey J (2010) First assessment of the male territorial vocal behaviour of a Malagasy leaf litter frog (*Gephyromantis thelenae*). *Herpetologica* 3, 141–150.
- Zweifel RG (1985) Australian frogs of the family Microhylidae. *Bulletin of the American Museum of Natural History* 182, 265–388. Available at <https://digitallibrary.amnh.org/items/e13048b0-5fc6-46bf-b5da-78d4a07bfd87>

Data availability. Data is available upon reasonable request.

Conflicts of interest. Authors have no conflict of interest.

Declaration of funding. This work was funded by the Holsworth Wildlife Research Endowment Grant (Ecological Society of Australia), the Skyrail Rainforest Research Fund (Skyrail Rainforest Foundation), and the Ric Natrass Research Grant (Queensland Frog Society Inc.).

Acknowledgements. We would like to thank Scott Macor, Laure Senor, David Woods, Jacopo Bartholomew, and Jacqueline Richmond-Clay for their help in the field. This research was conducted under James Cook University animal ethics approval A2945 and Queensland Government scientific research permits WA0057056. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the US Department of Agriculture. The USDA is an equal opportunity provider and employer.

Author contributions. Conceptualization: JG, MHMM, CJH. Developing methods: JG, MSS, MHMM. Data analysis: JG. Preparation of Figures and tables: JG. Conducting the research, data interpretation, writing: JG, MSS, MHMM, CJH.

Author affiliations

^ACollege of Science and Engineering, James Cook University, Townsville, Qld 4811, Australia.

^BDaniel K. Inouye US Pacific Basin Agricultural Research Center, United States Department of Agriculture, Agricultural Research Service, Hilo, HI 96720, USA.

^CMax Planck Institute of Animal Behavior, Department of Migration, Radolfzell 78315, Germany.