Remote sensor camera traps provide the first density estimate for the largest natural population of the numbat (Myrmecobius fasciatus)

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Remote sensor camera traps provide the first density estimate for the largest natural population of the numbat (*Myrmecobius fasciatus*)

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ABSTRACT

Context. Accurate estimates of population size is fundamentally important for effective conservation management of threatened species. Remote sensor camera traps often capture cryptic species that are difficult to sight or capture. When animals are individually identifiable, camera traps can be used in conjunction with mark–recapture methods to provide a robust estimate of density. This has been effective for medium and large mammals such as felid and quoll species. Less is known about whether this may be an effective approach for smaller species. The numbat (*Myrmecobius fasciatus*), a small diurnal marsupial once widespread across southern Australia, is now highly restricted. Low densities and crypsis make them challenging to survey, and current population monitoring methods (driving transects and sign surveys) do not provide accurate density estimates. **Aims.** This study aimed to: (1) assess whether numbats can be individually identified using camera trap images; and (2) use spatial and non-spatial capture–recapture methods to investigate whether camera trapping is a viable population monitoring tool for numbats in the largest extant population. **Methods.** We conducted spatial and non-spatial population modelling using images captured incidentally during a large camera-trapping project. **Key results.** We found numbats could be individually identified by stripe patterns from camera images that, in conjunction with capture–recapture modelling, could provide a density estimate. From 6950 trap nights there were 116 numbat detections on 57 of 250 cameras. Of these, 61 detections were used to identify 29 individuals and provide a density estimate of 0.017 $ha^{-1} \pm 0.004$ (CV = 0.26). This density applied across the estimated extent of distribution suggests a substantially larger numbat population in the Upper Warren, Western Australia (~1900 adults) than previously assumed. **Conclusions.** Camera trapping is a potential method for monitoring the population density of small uniquely marked species, such as the numbat, and for monitoring population trends in response to conservation efforts such as introduced predator control and translocations, as well as management actions such as prescribed burning and timber harvesting. **Implications.** This study contributes to the understanding of situations where camera traps can be utilised to survey small, cryptic species. To provide a more reliable density estimate, and to develop an optimal sampling layout for numbats, further studies would be required.

Keywords: conservation, endangered species, mammal, population density, spatially explicit capture–recapture (SECR), Western Australia.

Introduction

Accurate population density estimates are important for the effective management of species, particularly when they are of conservation concern. When a species has individually unique coat patterns, capture–recapture methods can be applied to image data from remote-sensor cameras to provide estimates of abundance and density (Karanth *et al.* 2004; Foster and Harmsen 2012; Efford and Fewster 2013). Advantages of camera traps include their ability to provide near continuous observations without the need for human presence, which means sample sizes and chances of detection can often be increased with reduced physical effort in monitoring (Silveira *et al.* 2003; Sollmann *et al.* 2011).

Accordingly, camera trapping is used extensively to estimate population densities of large carnivores that are elusive and occur at low densities (Foster and Harmsen 2012). Camera traps can also be highly effective at detecting smaller mammals (rodents, mustelids and marsupials; Glen *et al.* 2013), and there has been some success in estimating density for medium to small mammals with unique coat patterns such as the fox squirrel (Greene and McCleery 2016), american martin (Sirén *et al.* 2016) and northern quolls (Austin *et al.* 2017). These studies found that camera traps provided comparable population parameter estimates to live trapping. For fox squirrels, camera traps were preferable to live trapping because camera traps did not induce trap shyness, and so increased the rate of recaptures, resulting in a more precise density estimate (Greene and McCleery 2016). Refining the use of camera traps for different species (e.g. optimising survey design elements such as spatial arrangement, location, timing and duration of recording) can improve the efficiencies, quantity and quality of data collected and the information that it can provide. This is particularly valuable when working on rare and/or cryptic species that are a priority for conservation and management.

Robust density estimates can be derived using the spatially explicit capture recapture (SECR) modelling approach. SECR is a relatively new method of modelling populations that addresses some of the limitations of estimating population density using traditional capture–recapture methods, by modelling the distribution of home range centres and the probability of detection within a sampling area (Efford and Fewster 2013). The application of SECR requires detection of individuals at multiple locations, but removes the edge effect of sampling, allowing flexibility in sampling design (Efford *et al.* 2009; Rich *et al.* 2014).

Estimating population density can be challenging when a species is elusive, wide-ranging and solitary. One such species is the numbat (*Myrmecobius fasciatus*), a small (350–700 g), cryptic marsupial, distinctive in its diurnal habits, termitivorous diet and stripe patterns across the distal half of the back (Friend 1990; Cooper 2011). Once widespread across the arid, semiarid and some temperate parts of southern Australia, numbat populations declined dramatically since the introduction of invasive predators to Australia, and by the mid-1980s numbats were restricted to two isolated populations in Dryandra Woodland and the Upper Warren region (including Tone-Perup Nature Reserve, Kingston National Park and Palgarup State Forest) of Western Australia (Hayward *et al.* 2015). Although several populations have been reintroduced into areas within the species' former range, the global population estimate is fewer than 1000 mature individuals (Department of Parks and Wildlife 2017). The numbat is listed as endangered on the IUCN Red List (Woinarski and Burbidge 2016). The main causes of population decline are introduced predators, habitat fragmentation and changed fire regimes (Friend 1990). The negative impact of introduced predators is reflected in the success of populations reintroduced inside fenced havens or into areas with fox- and cat-baiting regimes (Department of Parks and Wildlife 2017; Radford *et al.* 2018).

The numbat population in the Upper Warren region is estimated to be the largest (from 200 to 500 mature individuals) but is relatively understudied compared with the Dryandra population (Calaby 1960; Christensen *et al.* 1984; Fumagalli *et al.* 1999; Department of Parks and Wildlife 2017; Threatened Species Scientific Committee 2018). The Upper Warren region includes over 140 000 ha of predominately contiguous jarrah (*Eucalyptus marginata*) forest, which is considerably different to the open woodlands or arid regions inhabited by other numbat populations. Numbats cannot be trapped using traditional live trap methods because their specialised diet means they are not attracted to bait. Monitoring methods developed for other populations include driving along tracks and recording sightings per 100 km, and surveys for evidence of sign (diggings and scats) to provide an index of population size (Friend 1990; Vieira *et al.* 2007; Department of Parks and Wildlife 2017). Driving surveys are impractical in the Upper Warren due to dense vegetation (and hence low visibility) and scarcity of tracks. In 1995 and 1996, driving surveys in the Upper Warren resulted in a sighting rate of 0.3/100 km and 1.45/100 km respectively (Department of Parks and Wildlife 2017). Further driving surveys in 2014 and 2015 produced no sightings (J. Wayne, pers. comm.). Opportunistic sightings have provided the greatest source of records for numbat presence in this region (Department of Parks and Wildlife 2017) (Fig. 1).

Although the above methods offer some indication of the abundance and distribution of the numbat, they have limitations, particularly when populations are small. The Numbat Recovery Plan highlights the need to develop a robust method to estimate population numbers for all subpopulations, and to monitor population responses to management strategies such as prescribed burning, predator control and translocation, particularly if populations are declining (Department of Parks and Wildlife 2017).

A large set of numbat images was obtained during a camera-trapping project designed to monitor the uptake of Eradicat® bait in the Upper Warren region (Wayne *et al.* 2019). We opportunistically used these data to (1) assess whether numbats can be individually identified using camera trap images, and (2) use spatial and non-spatial capture–recapture methods to investigate whether camera trapping is a viable population monitoring tool for numbats in the Upper Warren region.

Materials and methods

Study area

This study was confined to the main contiguous areas of public land managed by the Department of Biodiversity, Conservation and Attractions (DBCA) in the parts of the upper catchment area of the Warren River north of the Muir Highway, including Tone-Perup Nature Reserve,

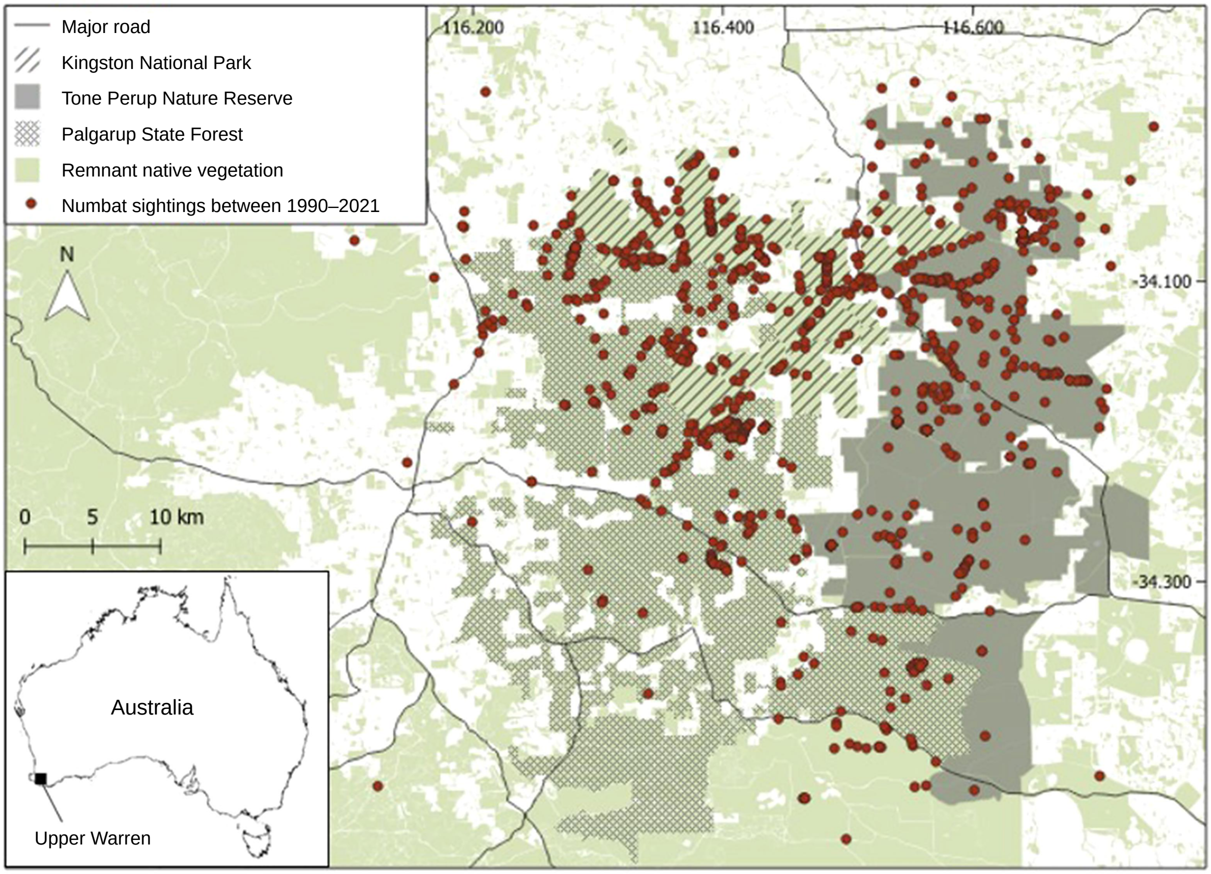

Fig. 1. Locations of numbat sightings ($n = 1068$) between 1990 and 2021 in the Upper Warren region, Western Australia based on records held by the Department of Biodiversity, Conservation and Attractions, Western Australia. Detections from this study are included.

Kingston National Park and Palgarup State Forest. This area constitutes the main (but not entire) area where numbats are known to occur within the region. The Upper Warren region consists of woodlands and forests dominated by tall jarrah (*Eucalyptus marginata*), marri (*Corymbia callophyla*) and wandoo (*Eucalyptus wandoo*) trees, and is situated approximately 300 km south of Perth, Western Australia. It is a major stronghold for many threatened and conservation-dependent fauna such as the numbat, woylie (*Bettongia penicillata ogilbyi*), ngwayir (*Pseudocheirus occidentalis*), tammar wallaby (*Macropus eugenii derbianus*), wambenger (*Phascogale tapoatafa wambenger*) and chuditch (*Dasyurus geoffroii*). The area is subject to management practices including prescribed burning, timber harvesting and fox control for conservation through poison (1080) baiting, and is largely surrounded by agricultural land (Department of Environment and Conservation 2012; Fig. 2).

Camera trap study design

Numbat images were collected as part of a larger project, The Southwest Threatened Fauna Recovery Project (Wayne *et al.* 2019). In brief, camera trapping was undertaken throughout the southern jarrah forest in south west Australia, between Nannup and Denmark, for the purposes of a bait uptake trial. Reconyx HC600 or PC900 cameras were deployed along 5-km transects offset between 5 and 20 m from forest tracks. Cameras were placed 100 m apart, totalling 50 cameras per transect at a height of 20–30 cm above the ground, depending on the slope of the site. Tracks were closed to vehicle traffic during the sampling period. Cameras were set to take 10 rapid fire images per trigger with no time delay between triggers. Dummy cameras were placed at the camera trap points for 3–4 weeks before trapping to reduce any impact on animal behaviour during the survey period. The total sample effort included 20 transects (design described above) and 20 smaller grids (total size 200 m × 40 m, not used in this study). The five transects that had numbat detections, and were sampled between October 2016 and February 2017 (i.e. considered as a closed population), were used in this study (Table 1). Each transect had a sampling period of 28 days per transect, except for one that had 29 days, reduced here to 28 days for consistency (Table 1; Wayne *et al.* 2019). This subsampling was selected

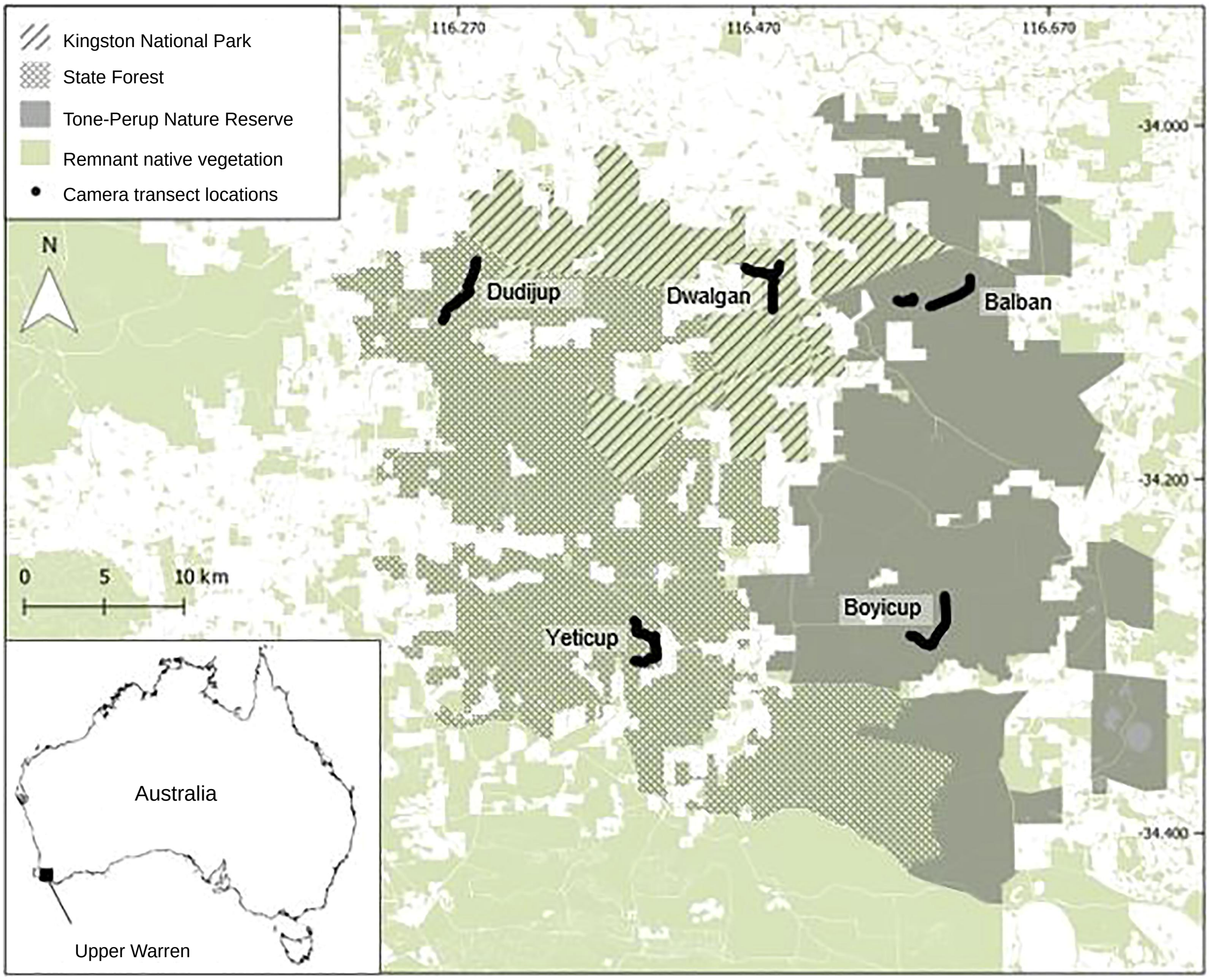

Fig. 2. Locations of five camera trap transects in the Upper Warren region.

Table 1. Transects used in this study, with the start and finish dates for the camera-trapping period.

Transect (forest block) name	Capture period
Balban	22/11/2016–20/12/2016
Boyicup	22/11/2016–20/12/2016
Dwalgan	18/10/2016–15/11/2016
Dudijup	18/10/2016–15/11/2016
Yeticup	4/01/2017–1/02/2017

to satisfy the assumption that the capture period was closed, while providing sufficient time for required recaptures.

Individual identification

Images were separated into independent detection events, defined as being at least 1 h apart. Low quality images with indistinguishable coat patterns (e.g. blurry, too distant) were discarded. For identification of individuals, and to account for asymmetrical coat patterns, multiple images in a trigger sequence were combined to include at least a left- and right-side image, as well as back and front images where possible. Single-sided detections were included if they could be matched to a detection with both sides of the numbat captured or were left side only. Right side only detections were excluded to prevent duplication of individuals. Each detection was given a unique identifier and recorded with the date and camera trap ID (Efford 2019*a*). All numbats had equal opportunity to be detected on camera and identified by stripe patterns (Fig. 3).

All detections were compared, and individual identification completed using stripe numbers and patterns. Individual identification was assessed by two observers to check consistency of identification. Four detections could not be agreed by both observers and so were removed from the analysis. No individuals were identified on more than one transect and all transects were considered independent because the distance between transects (between 7 and 25 km) was greater than the distance a numbat would travel within published home range estimates for this population (<123 ha) (Christensen *et al.* 1984).

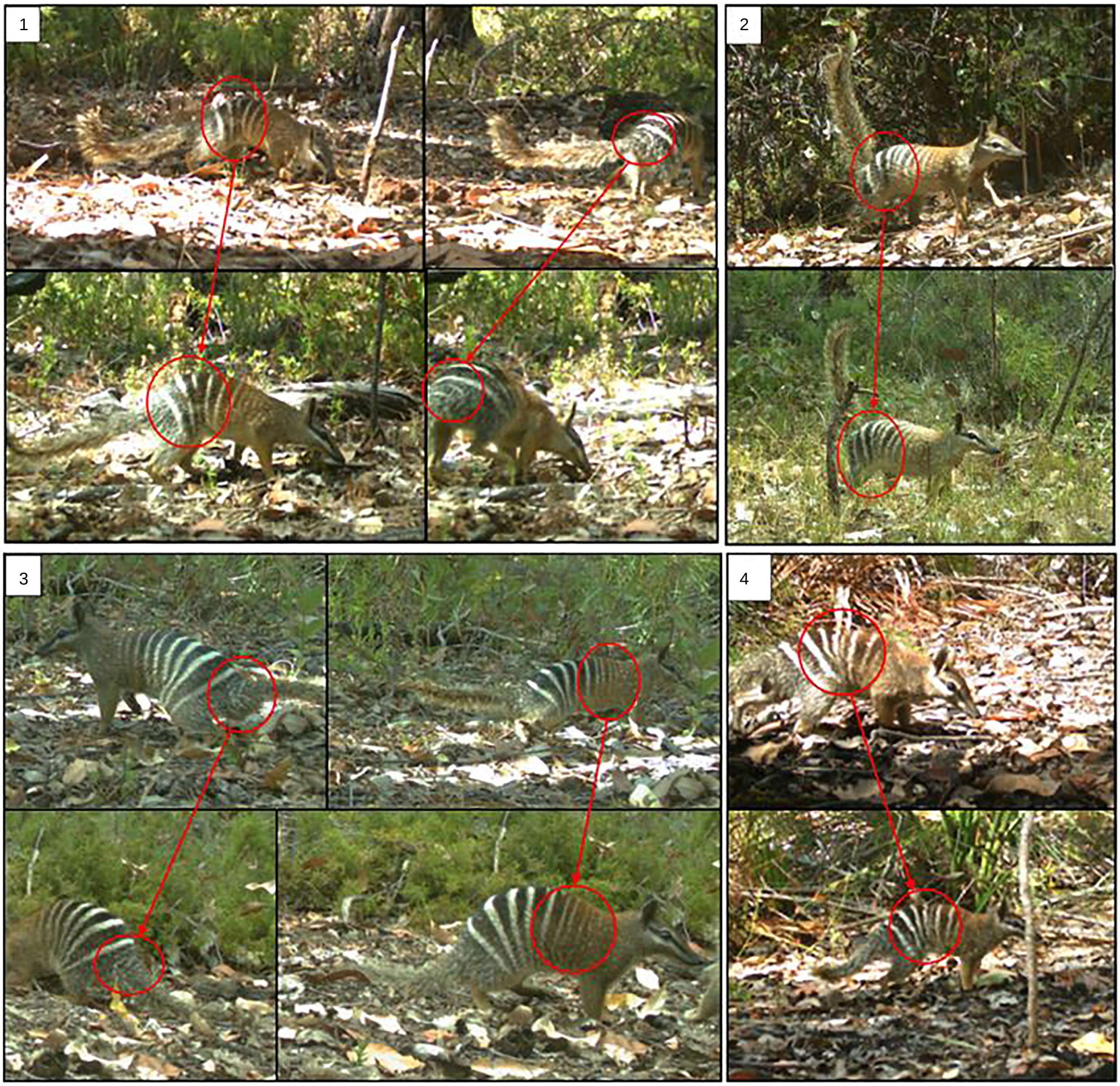

Fig. 3. Four examples of individual identification of numbats within this study, with red circles outlining the unique stripe patterns used for individual identification. Each numbat is labelled with a number.

Statistical methods

All statistical analysis was completed in program R version 3.6.1. Spatially explicit capture recapture analysis was completed in the SECR package (Efford 2019*c*) and non-spatial capture recapture was completed in openCR (Efford 2020).

Spatially explicit capture–recapture

The information for each detection was recorded in a capture matrix. Each transect was defined as an independent sampling session and each 28-day sampling session was divided into 7-day sampling occasions (Efford 2019*a*). This sampling period was selected to have adequate detections within each sampling occasion. A full likelihood SECR analysis with a 'count' detector was used to provide a density estimate for each transect. These data were then combined into a multisession full likelihood SECR analysis (Efford 2018), allowing data from independent sampling areas to be combined. A null model was compared to models where density (D), capture probability (g_0) and space use (σ) were varied by session, as well as applying half normal (HN), negative exponential (EX) and hazard rate (HR) detection functions. The models were compared using Akaike Information Criterion corrected for small sample size (AICc) and the model with the lowest value was selected as the best model. The validity of the detection functions were tested using an effective sampling area (ESA) plot (Efford 2019*b*).

A shapefile habitat mask outlining the core distribution of the numbat in the Upper Warren was created in QGIS 3.4.1. This is a contiguous block of DBCA-managed land, including Tone Perup Nature Reserve, Kingston National Park and Palgarup State Forest. A buffer of 700 m was applied to each transect, based on an average σ value for each transect. The buffer region is generally accepted to be 4σ, but should be large enough to cover the home range of all animals that may be detected (Efford 2017). The adjustment of the buffer region above 700 m in this study did not have a strong effect on the density estimate. Abundance was estimated by multiplying the density estimate by the estimated extent of distribution. The estimated extent of distribution was calculated by applying a naive occupancy estimate (83%) for the Upper Warren region (Seidlitz 2021) to the area calculated in the shapefile habitat mask (136 562 ha), resulting in an area of 113 346 ha. The naive occupancy estimate was obtained by sampling sites using a stratified random design to represent a range of forest type, harvest history, years since fire and fox-baiting regimes. Each site had eight 40 × 100 m plots for repeated surveys within different areas, placed a minimum of 1 km apart. The surveys were conducted between 8 October and 29 November 2018 on dry days only and were searched for sign for 30 min (Seidlitz 2021). This area included only DBCA-managed lands with native vegetation and no private property.

Non-spatial capture–recapture

Density was estimated by calculating abundance for each transect and dividing this estimate by the effective sampling area. The abundance was calculated for each transect using a Jolly-Seber-Schwarz-Arnason (JSSA) closed population capture recapture model in openCR, using the same capture matrix developed for the SECR model above. The effective sampling area was calculated using two methods: (1) half mean maximum distance moved (MMDM) using camera trap captures (Wilson and Anderson 1985); and (2) full MMDM using camera-trap captures (Parmenter *et al.* 2003). Each distance was applied as a buffer around the trapping grid and the effective sampling area was calculated in hectares using QGIS. The abundance estimate was divided by the effective sampling area to provide a density estimate for each transect. Density estimates for all transects were then averaged to estimate density for the Upper Warren region.

Results

Spatially explicit capture–recapture model

There was a total of 6950 trap nights across all transects and 116 numbat detections from 57 of 250 cameras. Of these, 61 detections were suitable to use in the SECR model, and 29 individual numbats could be identified. The number of individual numbats detected per transect ranged from three to eight. The best performing multisession SECR model was a null model with a negative exponential detection function (Table 2).

Density (D), capture probability (g_0) and sigma (σ) for all transects, along with the coefficient of variance (CV; used as a measure of precision) are shown in Table 3. Based on the average density, (0.017 ha^{-1} ± 0.004 (CV = 0.26)), the numbat population in this region is estimated to be ~1900 (95% CI: 1474–2380). This may also include dispersing subadults that are difficult to distinguish from adults.

Non-spatial closed population model

Non-spatial density estimates varied greatly depending whether half or full MDMM was used to define the effective sampling area. Non-spatial estimates generally had lower variance than spatial estimates at a transect level and do not violate assumptions because all animals have a non-zero chance of capture. The density estimates per hectare when averaged across all sites (half MDMM: 0.059 ha^{-1}; full

Table 2. AIC comparison of models fitted for a closed population multisession spatially explicit capture–recapture (SECR) model for numbat density in the Upper Warren region. Parameters in these models relate to density (D), capture probability (g_0) and sigma (σ).

Rank	Model	Detection function	No. of parameters	ΔAICc
1	{D~1, g_0~1, σ~1}	Exponential	3	0
	{D~1, g_0~1, σ~1}	Hazard rate	4	2.9
	{D~1, g_0~1, σ~1}	Halfnormal	3	3.8
2	{D~1, g_0~1, σ~(session)}	Exponential	7	4.3
3	{D~(session), g_0~1, σ~1}	Exponential	7	7.7
4	{D~1, g_0~(session), σ~1}	Exponential	7	8.1
5	{D~(session), g_0~1, σ~(session)}	Exponential	11	15.6
6	{D~1, g_0~(session), σ~(session)}	Exponential	11	19.8
7	{D~(session), g_0~(session), σ~1}	Exponential	11	20.5

Table 3. Numbat density (*D*) estimates per hectare for individual transects and for all transects combined using a full likelihood closed population multisession spatially explicit capture recapture (SECR) model with standard deviation (s.e.), coefficient of variance (CV), g_0 (capture probability) and σ (sigma) values.

Transect	*D* (s.e.) (ha^{-1})	CV	g_0 (capture probability)	σ
Transect 1 (Balban)	0.037 (0.02)	0.53	0.31	110.8
Transect 2 (Boyicup)	0.016 (0.01)	0.66	0.26	131.9
Transect 3 (Dwalgan)	0.051 (0.04)	0.85	0.16	87.9
Transect 4 (Dudijup)	0.006 (0.008)	1.21	0.39	176.9
Transect 5 (Yeticup)	0.0013 (0.006)	0.43	0.15	291.6
Multisession (all transects)	0.017 (0.004)	0.26	0.20	168.2

MDMM: 0.026 ha^{-1}) were larger than the SECR model, with the half MDMM estimate being more than triple the density per hectare. Transect-based estimates were inconsistent between SECR and non-spatial density estimates, but were most similar when using the full MDMM method to define effective sampling area (Table 4).

Discussion

This study illustrates that the density of a numbat population can be modelled using camera trapping and capture–recapture methods. This is important progress in the management of this high-profile but enigmatic species. Although camera traps have been used to obtain density estimates for medium to large mammals (Karanth *et al.* 2004; Sollmann *et al.* 2012; Sun *et al.* 2014; Kristensen and Kovach 2018) and some smaller mammals (Greene and McCleery 2016; Sirén *et al.* 2016; Austin *et al.* 2017), the numbat is perhaps the smallest mammal in the published literature to date to have derived robust density estimates using coat patterns to identify individuals from camera-trap images and SECR modelling. In doing so it demonstrates the potential suitability of this approach for a broad range of other small to medium-sized species.

Numbat densities derived from camera trapping and SECR modelling may be suitable as the standard method by which all numbat populations are assessed and monitored. Density estimates can be derived from distance sampling applied to detections from driven transects (Vieira *et al.* 2007), but low sighting rates in the Upper Warren suggest this is an inefficient method of sampling (Seidlitz *et al.* 2021). Advantages over the driven transect approach include being able to record adequate numbers of animals, even in habitats with relatively high vegetation density, and may be more cost effective per numbat detection (Seidlitz *et al.* 2021). Sampling for density estimates is also likely be more sensitive to changes in population trends than occupancy sampling, for example from sign surveys, becaue it is estimating number of individuals rather than just presence. With refinements, this camera-trapping method could assess numbat population-level responses to activities such as translocation, predator control, prescribed burns and timber harvesting, which has not previously been done in the Upper Warren (Wayne *et al.* 2017). To achieve sufficiently sensitive results to monitor such trends, and to improve sampling efficiencies, baseline parameters from this study should be employed to inform necessary study design simulations and power analyses (Green *et al.* 2020). Further, individuals can be sexed in some photographs and juveniles are distinguishable just after dispersal in December, meaning sex ratios, relative juvenile densities and recruitment rates could potentially be estimated. The high fidelity of numbats to an area also makes it possible to estimate survival with long-term sampling.

Our density estimate of 0.017 ha^{-1} ± 0.004 (leading to a population estimate of ~1900 based on 83% occupancy of DBCA-managed land within the Upper Warren region) is considerably higher than previous population estimates (from less systematic approaches) of between 100 and 200–500 mature individuals for the Upper Warren (Department of Parks and Wildlife 2017; Threatened Species Scientific Committee 2018). However, the density estimate derived in this study, and used to estimate the population size, is biologically plausible and comparable to the more arid habitats in the predator-free haven at Scotia Sanctuary, western New South Wales (0.017 numbats per ha) (Vieira *et al.* 2007). The density estimate is also consistent with estimates and assumptions based on home range size. Individual home ranges of up to 120 ha have been recorded in the Upper Warren (Christensen *et al.* 1984), and mean home ranges elsewhere have varied seasonally from 25 to 97 ha (Bester and Rusten 2009; Hayward *et al.* 2015). Radio tracking of 15 numbats in Dryandra and Boyagin Nature Reserve (Western Australia) resulted in an approximation of about four numbats (two male–female pairs) per 100 hectares in high quality habitat (Department of Parks and Wildlife 2017).

Such a substantial difference in the Upper Warren population estimates may have significant consequences for the conservation and management of the species and its habitat. However, this estimate should be viewed as indicative due to the opportunistic nature of this study. A more rigorous,

Table 4. Numbat abundance (n) and density estimates per transect with standard error (s.e.) and coefficient of variance (CV) values using a Jolly-Seber-Schwarz-Arnason full likelihood closed population capture–recapture model.

Transect	n (s.e.)	CV	Buffer calculation	Effective sampling area (ha)	Numbat density (s.e.) (ha^{-1})	No. of individuals	No. of recaptures
Transect 1 (Balban)	9.39 (4.32)	0.46	Half MMDM[A]	75.31	0.12	8	10
Transect 2 (Boyicup)			Full MMDM[B]	166.82	0.056		
Transect 3 (Dwalgan)	5.08 (2.68)	0.53	Half MMDM[A]	142.61	0.036	5	6
Transect 4 (Dudijup)			Full MMDM[B]	301.69	0.017		
Transect 5 (Yeticup)	6.43 (6.92)	1.08	Half MMDM[A]	74.52	0.086	6	3
Transect 1 (Balban)			Full MMDM[B]	164.07	0.039		
Transect 2 (Boyicup)	3.16 (1.84)	0.58	Half MMDM[A]	134.84	0.023	3	4
Transect 3 (Dwalgan)			Full MMDM[B]	286.1	0.011		
Transect 4 (Dudijup)	9.27 (3.98)	0.43	Half MMDM[A]	303.96	0.031	7	9
			Full MMDM[B]	1035.42	0.009		
All transects	33.33		Half MMDM[A]		0.059	29	32
			Full MMDM[B]		0.026		

Transects are labelled according to the forest block they were placed in.
[A]Half mean maximum distance moved using camera trap captures.
[B]Full mean maximum distance moved using camera trap captures.

numbat-specific framework should be applied to provide more robust and accurate estimates. More precise estimates of the population size with a higher degree of confidence can inform regulatory authorities, planners and managers of the potential significance that disturbance activities (such as fire, timber harvesting and habitat clearing) may have on numbat populations.

The relatively large population size in the Upper Warren also raises the possibility of it being a viable source population for future numbat translocations. Translocation from both wild and captive populations has proven to be a valuable tool in the conservation of this species, increasing both total population estimates and the number of self-sustaining populations (Friend and Thomas 1994; Hayward *et al.* 2015; Palmer *et al.* 2020). Accurate density and population abundance estimates can help determine safe harvest rates and be used to monitor populations harvested for translocation to verify that the harvests have been sustainable.

Density estimates derived from SECR are preferred over estimates derived from non-spatial methods. Although the non-spatial estimates generally had lower CV values within a transect, the density estimates were considerably higher. However, with uncertainty in the estimates of effective sampling area and no reliable way of determining whether these estimates were accurate, these density estimates are not regarded as reliable. Radiotracking estimates from this region are available (Christensen *et al.* 1984), but they were considered too variable to provide a reliable estimate of effective sampling area. This method could be applied if contemporary telemetry data were available to provide greater understanding of space use (Murphy *et al.* 2019). However, SECR models provide a solution without requiring telemetry data, in that spatial movements are incorporated into the modelling process (Borchers and Efford 2008). The high CV values for single transect SECR estimates indicate there were insufficient captures for a reliable estimate, but when collating all detections in a multisession model, the estimates improved substantially. An increase in detection histories of individuals (number of individuals and recaptures of the same individuals) would therefore improve the estimates, as would having improved spatial information (detections of the same individual at multiple locations) (Sun *et al.* 2014). This would be possible with a more tailored, species-specific sampling design (e.g. optimised camera setup, spatial arrangement of traps and duration and timing of surveys).

Traps arranged in grids or arrays are spatially more informative than transects. Determining the ideal spacing between camera traps requires a balance between obtaining multiple captures per individual and multiple individuals within the population (Borchers and Efford 2008; Sollmann *et al.* 2012). Spacings approximating $2\sigma_{\min}$ have been recommended and used for studies of large carnivores (Sollmann *et al.* 2012; Sun *et al.* 2014; Kristensen and Kovach 2018), and may be suitable for numbats. Random or carefully structured placement of trapping grids and trapping points within them should be done to avoid potential biases – for example, avoiding systematically putting traps near tracks if tracks potentially influence numbat habitat use.

The timing of sampling may also be important. For instance, sampling during the summer, when numbats are mating and have larger home ranges (Bester and Rusten 2009; Cooper 2011; Hayward *et al.* 2015; Department of Parks and Wildlife 2017), could inflate sigma estimates compared with other times of year. Estimates could be improved by sampling after the mating period, during February to May, when activity levels are still high but only adults will be detected, because young are small and attached to the mother (Cooper 2011; Wayne *et al.* 2019).

A further advantage of using camera traps is the ability to collect information on non-target species. When survey design has been carefully considered, there has been some success estimating densities for multiple species from one trap grid (Rich *et al.* 2019). Thus, camera-trap surveys in the Upper Warren have the potential to be applied to other threatened species and introduced predators, some of which also have unique coat patterns (e.g. chuditch and feral cats; *Felis catus*). Further, simultaneous observations of increases or declines in species numbers can have important management implications, for example in understanding the effect of introduced predator control on prey species. This is particularly important for the Upper Warren region, which has recently had rapid and significant declines in at least seven other native mammal species (Wayne *et al.* 2017).

This study demonstrates that numbat population density can be estimated using camera traps in combination with capture–recapture techniques. It advances current monitoring methods and provides a method to track changes in population size and responses to management practices such as predator control, prescribed burning and translocation. Our indicative population estimate of ~1900 numbats for the Upper Warren, based on a density estimate of $0.017\ \mathrm{ha}^{-1} \pm 0.004$, is substantially larger than current published estimates and boosts the projected size of the global population appreciably. However, due to the limitations of this study, this indicative population estimate should be viewed with caution and revised when the region has been more rigorously sampled for the purpose of obtaining a population estimate. We suggest using this study as a baseline to tailor a survey design for this, and other numbat populations, ultimately to provide robust global population estimates and to monitor population trends.

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Data availability. The data that support this study will be shared upon reasonable request to the corresponding author.

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