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# Evaluating the use of thermal imaging cameras to monitor the endangered greater bilby at Astrebla Downs National Park

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**Abstract.** Spotlight surveys are widely used to monitor arid-zone-dwelling species such as the greater bilby (*Macrotis lagotis*). These surveys require a sufficient sample size to adequately model detection probability. Adequate sample sizes can be difficult to obtain for low-density populations and for species that avoid light and or have poor eyeshine like the bilby. Abundance estimates based on burrow counts can be problematic because of the variable relationship between the number of burrows used and bilby abundance. In 2013, feral predators devastated a Queensland bilby population and a method was required that could locate and monitor the remaining bilbies. We report on a study that compared density estimates derived from spotlighting and thermal cameras. Bilbies were surveyed annually over three years, using spotlights and thermal cameras on different nights but using the same transects to compare the methods. On average, thermal cameras detected twice the number of bilbies per kilometre surveyed than spotlighting. Despite this difference in the number of bilbies detected, density estimates (bilbies km$^{-2}$) were similar (thermal camera versus spotlight: 0.6 versus 0.2 (2014), 3.4 versus 3.4 (2015) and 4.8 versus 3.3 (2016)). Nevertheless, the larger sample size obtained using thermal cameras gave greater confidence in modelling detection probability.

**Additional keywords:** line transect, multiple-covariates distance sampling, threatened species

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## Introduction

Spotlight surveys using vehicles are widely used to estimate animal abundance cost-effectively and line transect methods (Buckland *et al.* 1993) allow detection probabilities to be calculated to adjust raw counts to estimates of density. Line transect surveys are particularly useful for surveying large areas. However, line transect methods require a sufficient sample size (>60: Buckland *et al.* 1993) to adequately model detection probability and account for observations that were missed (Buckland *et al.* 2015), which can be problematic for species that occur at low densities, such as the greater bilby (*Macrotis lagotis*). Furthermore, some mammal taxa, like bilbies, rarely look towards a spotlight, or have poor eye-shine, making their detection with a spotlight difficult (Focardi *et al.* 2001). For burrowing species such as bilbies, the proportion of time that animals are above ground and available for detection also needs to be determined to allow an estimate of density for the entire population to be made (e.g. Swann *et al.* 2002).

Thermal imaging cameras detect thermal energy in the long-wave, infrared spectrum emitted from all objects. Because they detect emitted heat radiation and do not need an additional illumination source, thermal imaging cameras may provide a more effective tool for detecting mammals and some birds in comparison to spotlights. The lack of a need for an additional illumination source also likely reduces the amount of disturbance to animals and therefore increases the amount of time that cryptic and or burrowing animals spend on the surface in comparison to when they are disturbed by light from spotlights. The increasing availability and reduced cost of thermal imaging systems means that they are likely to have further application in ecological studies and researchers have begun testing detection rates for different wildlife species (Focardi *et al.* 2001; Cilulko *et al.* 2013; McCafferty 2013; Ruttinger *et al.* 2014).

The bilby is a medium-sized (1–1.2 kg) (Johnson 2008), arid-zone-dwelling marsupial that is currently listed as *endangered* under the Queensland *Nature Conservation Act 1992*, *vulnerable* under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* and *vulnerable* by the International Union for Conservation of Nature. The species was once widespread across arid and semiarid Australia, including fossil records from caves near Rockhampton in central Queensland (Hocknull *et al.* 2007). It now occurs naturally in restricted and fragmented populations in the deserts of Western Australia, Northern Territory and Queensland (Southgate 1990; Moritz *et al.* 1997). Individuals are usually solitary and rely on a network of burrows to seek refuge during the day and escape predation at night (Moseby and O'Donnell 2003; McRae 2004; Pavey 2006).

The conservation of bilbies in Australia has been hampered by our inability to reliably assess population size and change at a scale that is appropriate to all areas (Southgate *et al.* 2005; Bradley *et al.* 2015; Cramer *et al.* 2017). The need for an effective survey method that is able to survey bilbies at an appropriate scale was highlighted in 2013 when feral cats and wild dogs devastated Queensland's largest bilby population at Astrebla Downs National Park (Astrebla) in south-western Queensland (Rich *et al.* 2014). Over 3000 cats were culled (2948 were shot) between April 2012 and December 2016 across the 176 000-ha reserve. Thirty-two wild dogs were also shot and more were baited in 2013. Analysis of stomach contents of the cats and dogs that were shot revealed they were both heavily preying on bilbies (Rich *et al.* 2014). Conservation managers at the time needed a survey method that could locate bilbies and monitor the abundance of the bilby population following predator control.

Trapping of bilbies is difficult and has animal welfare concerns, and it is not feasible to trap over a large area (Southgate *et al.* 2005; Smith *et al.* 2009; McGregor and Moseby 2014). Populations can also occur at very low densities, making it difficult to obtain a sufficient sample size for mark–recapture estimates of population size. For these reasons a non-invasive technique was sought. Remote cameras could be used to estimate occupancy or density (e.g. Ramsey *et al.* 2015), but the large number required to sample areas the size of Astrebla would be impractical.

Southgate *et al.* (2005) reported that burrow counts were ineffective at estimating the size of a bilby population at a fine scale. This is mainly due to the difficulty in knowing the relationship between the number of burrows and the number of bilbies (Lavery and Kirkpatrick 1997; Moseby and O'Donnell 2003; Southgate *et al.* 2005, 2019). An individual bilby can use up to 18 burrows concurrently over several months (Southgate and Possingham 1995; Moseby and O'Donnell 2003). Instead, aerial surveys, combined with surveys of bilby spoor (bilby tracks, scats and burrows), were found to provide reliable information on the extent of occurrence and the density of bilby populations at a broad scale (Southgate *et al.* 2005, 2019).

McRae (2004) converted aerial counts of active, or currently used, burrows to estimate population size by dividing the total number of burrows by the mean number of burrows used by an individual bilby as determined by radio- telemetry. Due to the variability in burrow usage by individual bilbies and problems associated with burrow detection from the air, the method may be limited to providing indices of abundance to track broadscale changes over time.

More recently, a 2-ha plot-based method (Southgate *et al.* 2005, 2019; Southgate and Moseby 2008) has become the technique of choice to survey for the presence or absence of bilbies (Bradley *et al.* 2015; Paltridge 2016; Cramer *et al.* 2017) and has been used to monitor a variety of species in arid parts of Australia (Pedler *et al.* 2016). For that method, only tracks, scats and diggings into the base of acacia shrubs, either by themselves or in combination, are considered definitive evidence of the presence of bilbies (Southgate *et al.* 2019). However, bilby habitat in south-western Queensland differs from that elsewhere in its present range, with more open vegetation and different soils. At Astrebla, the substrate makes it difficult to identify and age tracks, bilbies do not feed at the base of acacia shrubs and bilby scats are hard to detect in soil that is a similar colour and they are often removed rapidly by ants. Therefore, none of the three characteristics required to confirm the species' presence with the 2-ha plot-based method can be readily used with confidence at Astrebla.

Smith *et al.* (2009) and Carpenter and Dziminski (2017) successfully extracted bilby DNA from scats collected near burrows. Carpenter and Dziminski (2017) reported that sufficient DNA could be amplified from scats to monitor population size over time. In 2015, the 'Greater Bilby Recovery Summit' recognised the potential for using scat DNA to estimate population size, but emphasised the need for a more effective monitoring program that could 'demonstrate both national trends in the wild bilby population and the effectiveness of on-ground actions in reducing threats' (Bradley *et al.* 2015). It was suggested that while area of occupancy can provide some measure of population trend more broadly, no single technique was suitable for all habitats, as spoor could be difficult to find in some soil and vegetation types and under some conditions (i.e. high plant cover and after rainfall).

In 2014, the Queensland Parks and Wildlife Service began a three-year trial to compare spotlighting with thermal imaging to determine which of the two methods was the more accurate, reliable and cost-effective way of estimating bilby density at a scale relevant to park management. We report on the results of this trial and provide recommendations for future work that is likely to involve combining data from ground-based surveys and aerial counts of burrows.

## Material and methods

### Study area

Astrebla is located 100 km east of Bedourie in the Mitchell Grass Downs and Channel Country bioregions and covers an area of ~176 000 ha (Fig. 1). The Park was gazetted to protect the largest portion of the bilby population in Queensland, an area that also contains core habitat for other rare and threatened species, including the kowari (*Dasyuroides byrnei*) and plains-wanderer (*Pedionomus torquatus*). Astrebla is located in an arid environment with highly variable rainfall resulting in marked variation in primary production and, consequently, visibility (Fig. 2).

The study area was located in the northern section of the park and encompasses an area of ~1000 km$^2$. The clay plains, which contain a variable amount of stone and vegetation cover, dominate the landscape. The soil in these clay plains is usually soft, often deep-cracking, and ashy. A variety of annual and perennial grass and chenopod species dominate but the amount of ground cover varies seasonally and some patches are naturally more vegetated than others. The patches with the highest amount of stone cover are usually very sparsely vegetated. Mitchell grass species (*Astrebla* spp.) and button grass (*Dactyloctenium radulans*) are the dominant grass species. In good times, the clay plains can resemble a wheat field, which can transition to bare earth as conditions deteriorate. Small ironstone flats on clay

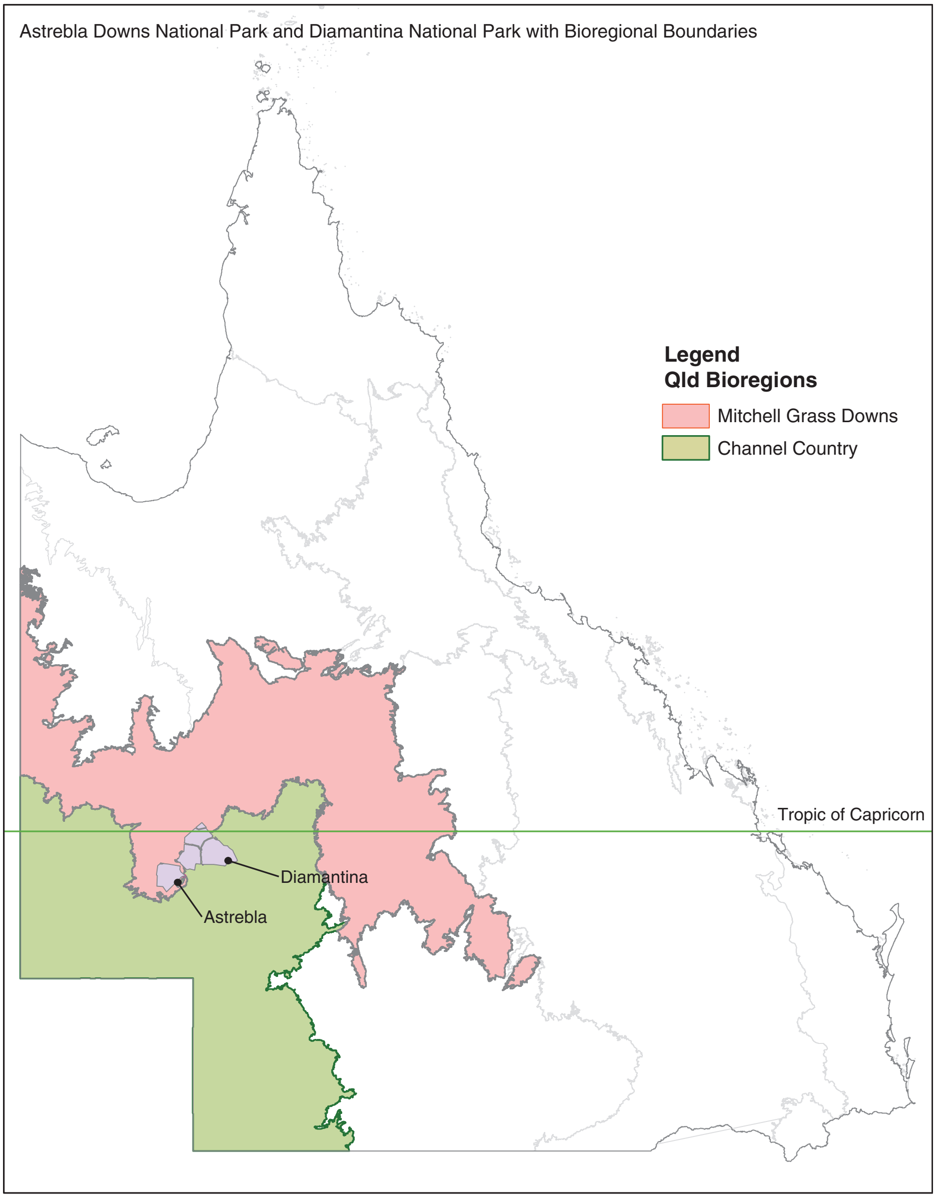

**Fig. 1.** Map of Queensland with bioregional boundaries and the location of Diamantina National Park and Astrebla National Park.

plains are also present and these are bare most of the time. The soils with a high stone content are often quite hard and resistant to the recording of bilby tracks. The whole study area is intersected by seasonal drainage lines that may contain trees, shrubs or dense grass.

### *Survey design*

Line transect surveys were carried out at Astrebla in May 2014, April 2015 and August 2016 using two observers standing in the tray of a motor vehicle travelling at ~10 km $h^{-1}$. Surveys commenced ~30 min after sunset. A GPS and a MP3 data recorder were used to record the location of all animals observed. Animals detected by thermal imaging cameras were identified using a spotlight (100 W). The same spotlights were used for the spotlight-only surveys. A rangefinder was used to measure the perpendicular distance from the vehicle to the location where the animal was first observed.

The thermal camera surveys were conducted using two FLIR MD-625 compact, fixed-view, marine thermal cameras mounted on each side and at the top of the vehicle's headboard (Fig. 3). The cameras were mounted at the top of the headboard to increase the chance of seeing over and through the grass tussocks. Each camera was connected to its own monitor (Kogan KALED16XXXWB 16″ LED screens) which was also mounted to the headboard so that there was one screen per camera and observer. A single control puck was used to control the amount of detail and the colour spectrum of the image (=the mode) to suit the individual observer's preference. The

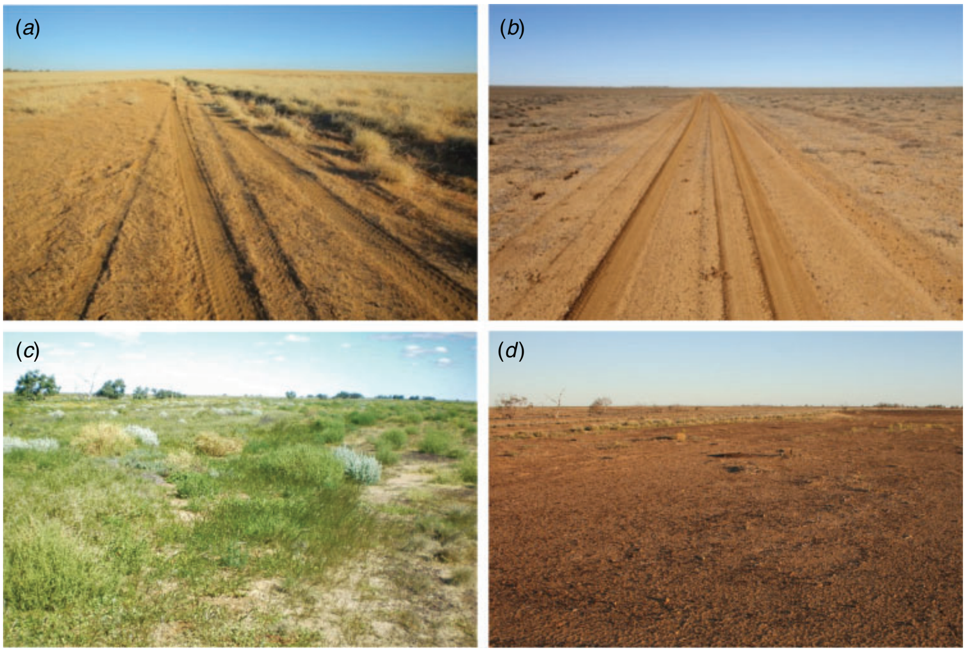

**Fig. 2.** Photographs of the clay plain habitat and how much the vegetation cover can vary. (*a*) Photograph taken in 2014 showing a relatively high grass biomass and cover, (*b*) photograph taken at approximately the same location in 2016 when there was little grass cover in a dry year, (*c*) photograph taken south of Backwards Creek in 2011 following above-average rainfall (photograph by Maree Rich) and (*d*) photograph taken at the same location south of Backwards Creek in 2016 following a period of below-average rainfall (photograph by Maree Rich).

**Fig. 3.** Photograph of the thermal image cameras mounted to the headboard of a tray-back vehicle.

'White = Hot' mode was used in 2014 and the 'black = hot' mode was used in 2015 and 2016, which simply refers to the colour of an object on the screen that is hot relative to other objects in the scene. Objects that were cooler were in shades of the opposite colour (i.e. in the case of the White = Hot mode the colour of the cooler objects were black to dark grey; refer to Appendix S1, available as supplementary material). The modes do not alter the illumination of an object and so changing from

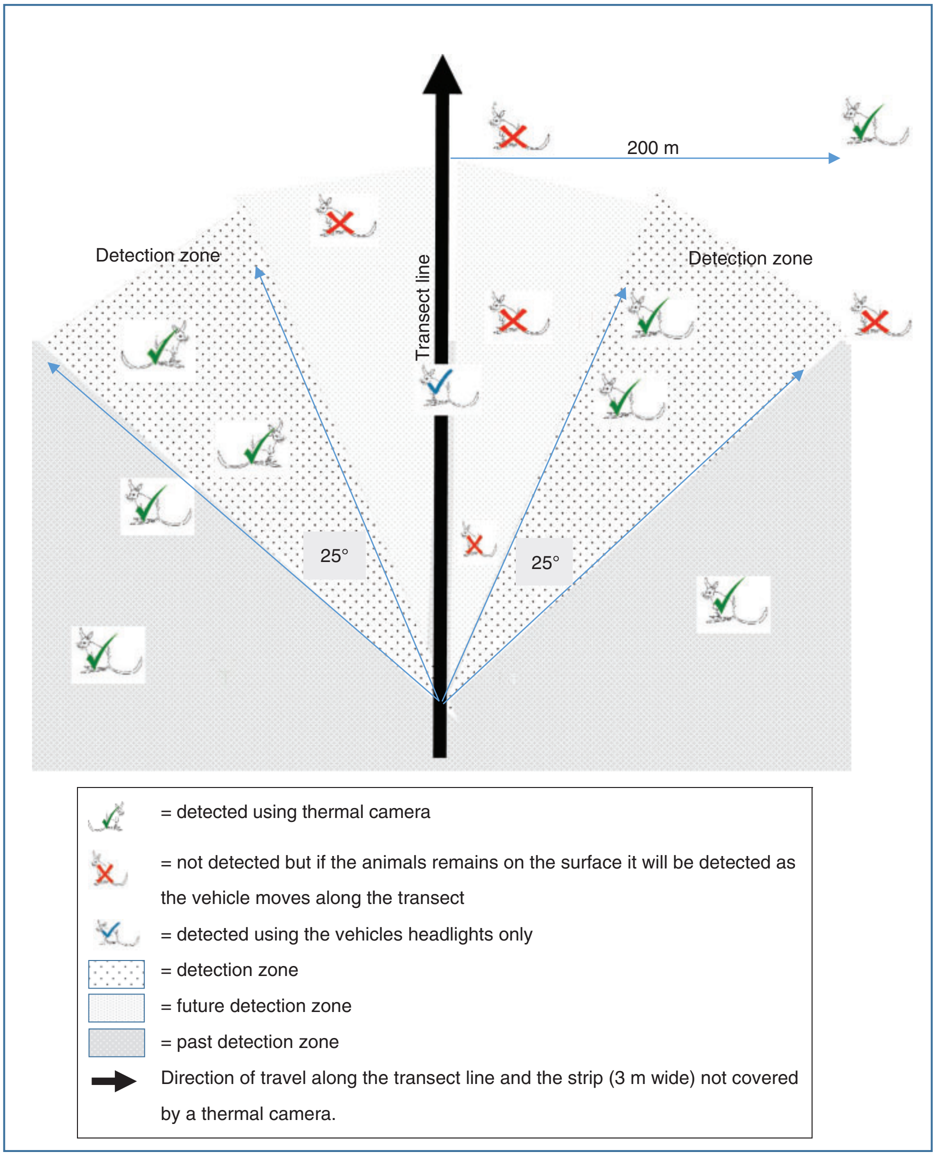

**Fig. 4.** Schematic diagram showing the thermal camera's detection zone.

one to the other was based on the individual user's preference and was not thought to alter detectability. The cameras provided 25° field of view and were positioned facing slightly forward and down so that the horizon was just visible at the top of the screen. This was done for two reasons. First, it reduced the speed at which the scene passed on the screen, thereby increasing the chance of observing an animal compared to the camera facing perpendicular. Second, distant animals were detected before they had a chance to move (an important assumption of line transect sampling: Buckland *et al.* 2001). Due to the angle of the thermal camera relative to the transect line, bilbies on the line and some bilbies near the line were initially detected using the vehicle's headlights. This ensured that animals were again recorded at their initial location and were not missed on the line. As the vehicle moved forwards, bilbies near the line that remained on the surface eventually moved into the thermal camera detection zone (Fig. 4).

To compare spotlighting with thermal imaging, two transects, Mooradonka (50 km) and Kite Drive (32.7 km), were surveyed twice each year from 2014 to 2016 inclusively – once with a spotlight and once using thermal cameras (Fig. 5). Two samples of a third transect (Curica Creek, 29.4 km) were obtained in 2014, once with a spotlight and again the following night using the thermal cameras. The habitat for these three transects was similar with the exception of transects adjacent to the drainage lines (see Appendix S2 in the supplementary material). The vegetation within the drainage lines adjacent to the Curica Creek and Kite Drive transects contained mature coolabah trees (*Eucalyptus coolabah*) while the drainage lines along the Mooradonka transect contained mixed shrub species often dominated by gundabluie (*Acacia victoriae*). Outside these drainage lines the landscape varied between a moderately dense grassland and sparse forbland but, in terms of visibility, was a fairly homogeneous mix of the two forms.

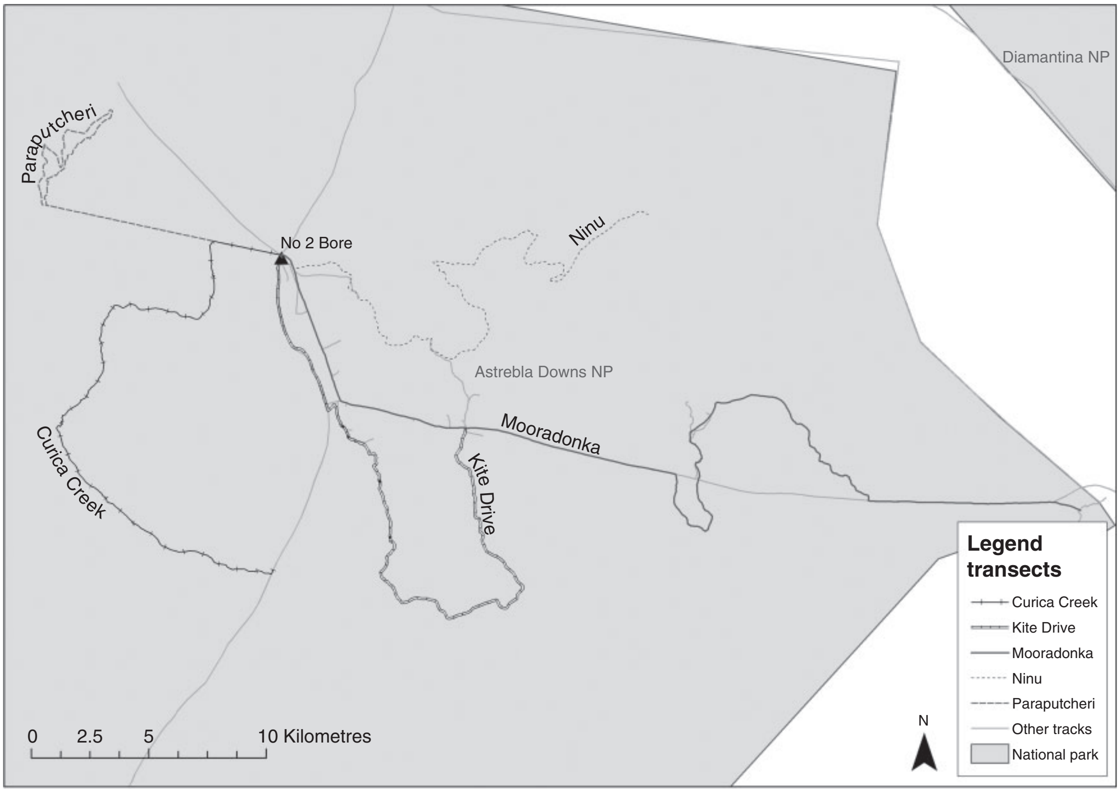

**Fig. 5.** Transects that were surveyed between 2014 and 2016.

In 2015 and 2016 some transects were surveyed once using only thermal imaging cameras in order to broaden the search for bilbies and contribute to overall density estimates in the time that was available. In 2015 these were the Curica Creek, Ninu (31.5 km) and Paraputcheri (24.9 km) transects, and in 2016 the Ninu transect. The habitat for the Ninu and Paraputcheri transects was similar to that of the other three, with a fairly homogeneous mix of grasslands and forblands away from the occasional drainage channel lined with trees or shrubs.

The order in which survey methods were conducted was alternated among transects in case surveying affected bilby behaviour the following night. For example, in 2015 spotlighting was conducted on the first night and thermal cameras were used on the second night to survey the Kite Drive transect. Thermal cameras were used on the first night followed by spotlighting on the second night for the Mooradonka transect.

### *Statistical analysis*

Initially, as recommended by Buckland *et al.* (1993), histograms of perpendicular distances were examined for evidence of violations of assumptions of distance sampling (e.g. reactive movement, heaping data at particular distances), for outliers, and to determine appropriate truncation levels. Truncation can simplify modelling of the detection function, improve model fit, reduce bias and improve precision. To compare spotlight and thermal camera methods, densities were calculated for transects in common (Mooradonka and Kite Drive). A separate analysis was then carried out for all transects surveyed using thermal cameras in 2015 and 2016 to estimate density across the study area.

Line transect data were analysed using multiple-covariates distance sampling (MCDS) in DISTANCE 7.2 (Thomas *et al.* 2010). MCDS has potential advantages over conventional distance sampling (CDS) when modelling detection probability with small sample size (Marques *et al.* 2007). In this study, strata were different years (YEAR: 2014, 2015 and 2016) and survey methods (METHOD: thermal, spotlight), which were included in the analysis as factor covariates. Detection probability was expected to differ between years because of greater grass cover in 2014 and 2015 than in 2016. Observers differed in their experience, so OBSERVER was also included as a factor covariate. It had two levels, contrasting the detection probability of an experienced observer (JA) on the right-hand side of the vehicle with the combined detection probability of less experienced observers (OP) on the left-hand side.

For MCDS, detection probability was modelled using a key function and up to two series-adjustment terms, as recommended by Marques *et al.* (2007). The models (half normal key plus Hermite adjustment, hazard rate key plus cosine adjustment) were compared using Akaike's information criterion (AIC). Separate models were fitted with different combinations of the three covariates, YEAR, METHOD and OBSERVER.

CDS was used to model detection probability pooled across strata and separately for each stratum. Following the recommendations of Buckland *et al.* (1993), three models were considered in the analysis, with each model comprising a key function that may be adjusted with a series expansion containing up to five parameters (which, by default, were added

**Table 1. The number of bilby sightings (untruncated) and sightings per hour by survey method and year**

The number of hours to obtain 60 sightings (i.e. a sufficient number to model detection probability) is also shown and the associated cost. Data are based on the Mooradonka and Kite Drive transects. Costs represent the add-on costs and do not include labour, fuel included as a component of the vehicle lease or vehicle lease costs. They are based on surveying 6 h per night, requiring three staff at $135 per person per day (travel allowance) and fuel at $30 per day (additional fuel cost required to operate in a remote area)

| | No. of sightings | | Sightings per hour | | Hours for 60 sightings | | Cost for 60 sightings (AU$) | |
|---|---|---|---|---|---|---|---|---|
| Year | Spotlight | Thermal | Spotlight | Thermal | Spotlight | Thermal | Spotlight | Thermal |
| 2014 | 1 | 7 | 0.1 | 0.4 | 600 | 150 | 43 500 | 10 875 |
| 2015 | 27 | 42 | 3.4 | 4.4 | 18 | 14 | 1305 | 1015 |
| 2016 | 59 | 118 | 7.3 | 11.1 | 8 | 5 | 580 | 363 |

sequentially). The models were a uniform or hazard-rate key function with a cosine or a polynomial series expansion, and a half-normal key function with a Hermite polynomial. AIC was again used to select the best model, but models with unrealistic spikes at zero distance, rather than a distinct 'shoulder' near the line, were disregarded. The MCDS and CDS models were compared using AIC to select the best model for estimating density.

Distances were measured by a rangefinder so were analysed as exact rather than grouped into intervals. Data were pooled across transect lines to model detection probability. Confidence intervals (95%) were calculated using a non-parametric bootstrap with 999 resamples, but the density estimate was taken from the original dataset (Buckland *et al.* 1993, 2015). Each transect was divided into 3–5 'legs' or subtransects to provide replicate lines for variance estimation. Start- and endpoints of subtransects were at marked changes in the landscape such as drainage lines or changes in topography. Data were analysed as clusters, although sightings comprised mostly single bilbies and occasionally two.

Estimates of bilby density ($D$) were determined as

$$D = [n/(2L\mathrm{wP})] \times \mathrm{cs}$$

where $n$ is the number of sightings of clusters of bilbies, P is the probability of detecting animals in the strip 2w, $L$ is the total length of the survey transect, w is the half-width of the strip (e.g. maximum distance sightings are made from the line or the truncation distance) and cs is mean cluster size (Buckland *et al.* 1993).

## Results

Thermal cameras were more effective at detecting animals than spotlights in most habitats. Across the three years, thermal surveys recorded approximately twice the number of bilby sightings than spotlight surveys (Table 1). Thermal surveys were consequently cheaper than spotlight surveys to obtain sufficient sightings for density estimation; considerably so in 2014 when bilbies were at very low densities. The initial cost (AU$5000 per camera) and the depreciation of the thermal cameras are not included in the calculation in Table 1 but, based on the cameras used in this trial, it is likely that the technology should last for at least five years and be able to complete at least 60 survey-hours per year. The add-on costs included in Table 1 do not include fixed costs such as vehicle lease and fuel costs and staff wages. These costs represent the costs of undertaking the survey that are in addition to the normal organisational operating costs that are budgeted for, irrespective of whether the survey occurs or not.

### Density estimation 2014

Sample size in 2014 was small for both thermal ($n = 6$, untruncated) and spotlight ($n = 1$) surveys on the Mooradonka and Kite Drive transects and so data were pooled with the 2015 data, when vegetation cover was similar. This enabled detection probability to be modelled for 2014 using the pooled 2014–15 data and density estimated for 2014. Densities for 2015 and 2016 were determined separately (see below). Given the small sample size in 2014, only METHOD was included as a covariate in the MCDS analysis. The model preferred by AIC had different detection functions for the two methods. There was a much steeper decline in detection probability for spotlight surveys (Fig. 6) and thus lower detection probability in a strip of w = 120 m. Moderately dense grass cover grew in 2014 and 2015, following moderate rainfall. A higher bilby density was estimated by the thermal survey but, not surprisingly given the low sample size, confidence intervals were broad (Table 2).

### Density estimation 2015–16

Small sample size again required combining data for 2015 and 2016 for analysis (Table 3). Only four bilbies were recorded across all transects on the centreline in thermal surveys in 2015 and 2016 and these were allocated alternately to left and right observers for analysis. The model with separate detection functions in each stratum (CDS Model 1) had the lowest AIC (Table 3). However, sample size was <60 in three strata and so MCDS Model 2, which had a similar AIC, was preferred. All three covariates (OBSERVER, YEAR and METHOD) were included in this model and the differences in detection probability between factor levels plotted. Thermal surveys had a flatter detection function than spotlight surveys resulting in higher detection probabilities and larger sample sizes (Fig. 7*a*). There was a steeper decline in detection probability in 2015 when animals were obscured by greater grass cover (Fig. 7*b*). The higher detection probability in 2016 meant that the density increase over 2015–16 was not as marked as the increase in encounter rate (i.e. sightings km$^{-1}$). In 2016, reduced ground cover due to low rainfall increased visibility, particularly on the sparsely vegetated clay plains, with bilbies being detected using thermal cameras out to 200 m in these areas.

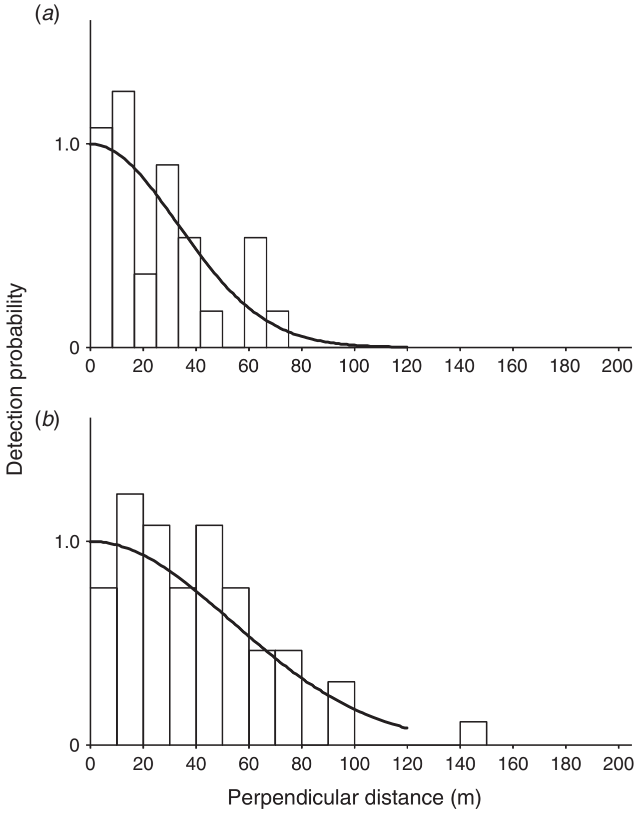

**Fig. 6.** Frequency histogram of bilby clusters sighted in surveys using (*a*) spotlights and (*b*) thermal cameras on the Mooradonka and Kite Drive transects in 2014–15. The number of sightings is scaled to the *y*-axis. The modelled detection functions using data truncated at 120 m are superimposed.

**Table 2. Bilby density estimates (95% CI), truncated sample size (*n*) and detection probabilities (*P* (95% CI)) from spotlight and thermal line transect surveys in 2014, 2015 and 2016 on the Mooradonka and Kite Drive transects**

*P* was determined for 2014 based on data pooled over 2014–15 (see text for details). *P* was determined for 2015 and 2016 based on data pooled over 2015–16 using Model 2 in Table 3. Total line length (L) for each survey was 82.7 km and truncation distance (w) was 120 m

| Method | Year | *n* | *P* (95% CI) | Density (95% CI) |
|---|---|---|---|---|
| Spotlight | 2014 | 1 | 0.35 (0.25–0.48) | 0.15 (0.00–1.98) |
| Spotlight | 2015 | 27 | 0.40 (0.29–0.55) | 3.41 (0.73–8.05) |
| Spotlight | 2016 | 49 | 0.77 (0.67–0.89) | 3.26 (1.23–6.37) |
| Thermal | 2014 | 6 | 0.55 (0.27–1.00) | 0.55 (0.15–2.02) |
| Thermal | 2015 | 40 | 0.61 (0.50–0.76) | 3.37 (0.43–6.31) |
| Thermal | 2016 | 87 | 0.96 (0.91–1.00) | 4.84 (1.65–8.47) |

**Table 3. Model selection for analysis of spotlight and thermal line transect data from surveys in 2015 and 2016 on the Mooradonka and Kite Drive transects**

Analysis in DISTANCE was undertaken using multiple-covariates distance sampling (MCDS) and conventional distance sampling (CDS) using key functions half normal (HN), hazard rate (HR) or uniform (U). Simple polynomial adjustment terms (P) were selected in two models, otherwise no adjustment terms were incorporated. For CDS, the detection function (DF) was modelled at the resolution of each of four strata (strata = method by year) or pooled across strata (global). For MCDS, combinations of three covariates were included in the model: M, method (thermal, spotlight); Y, year (2015, 2016); O, observer (JA, OP). Models are sorted by differences in Akaike's Information criterion (ΔAIC) between each model and the model with the lowest AIC value

| No. | Analysis | Covariates or DF resolution | ΔAIC | Key function (adjustment terms) |
|---|---|---|---|---|
| 1 | CDS | Strata | 0.00 | HN, U(P), HN, U |
| 2 | MCDS | M, Y, O | 0.78 | HR |
| 3 | MCDS | M, Y | 4.15 | HN |
| 4 | MCDS | Y, O | 6.17 | HN |
| 5 | MCDS | Y | 10.67 | HN |
| 6 | MCDS | M, O | 22.36 | HR |
| 7 | MCDS | M | 23.16 | HR |
| 8 | MCDS | O | 27.17 | HR |
| 9 | CDS | Global | 29.51 | U(P) |

The more experienced observer (JA) had a much flatter detection function than the less experienced observers (OP) (Fig. 7*c*), particularly for the thermal surveys. However, densities estimated separately for the two observers were similar (Table 4). The experienced observer recorded 8–16% more animals in 2015 and 35–42% more animals in 2016. These were mostly at greater distances, but the disparity in 2016 was mostly lost following truncation. Though not shown, similar densities were estimated when data were not truncated.

Detection using thermal imaging cameras was more difficult in areas with thick grass, or large cracks in the soil that radiated heat, in comparison to bare ground (authors' obs.). The cracks in the soil retained and radiated a lot of heat, sometimes as much as the mammals themselves. Detection with the thermal cameras improved as the night temperature cooled (~1.5 h after sunset), increasing the difference in temperature between the animal and its environment.

The frequency histogram of sightings for the thermal survey in 2016 has a broad mode at 50–70 m (Fig. 8*a*), suggesting that bilbies were either being missed closer to the line or that bilbies were taking evasive action and possibly retreating to burrows in response to the vehicle. This problem was not evident in the spotlight data for 2016 (Fig. 8*b*).

A higher density of bilbies was estimated by thermal rather than spotlight survey in 2016, but estimates were almost identical in 2015 (Table 2). Confidence intervals encompassing point estimates of density indicated no significant difference between 2015 and 2016 densities using either method, but there was a significant increase in density from 2014. Densities across the broader study area were comparable to that on the Kite Drive and Mooradonka transects (Table 5).

### Other fauna

Although the detection of other species was not a direct objective of this study, thermal imaging detected more small mammals than did spotlighting. A list of fauna encountered on all transects (not just the ones used to compare spotlighting with thermal imaging) for each year is provided in the

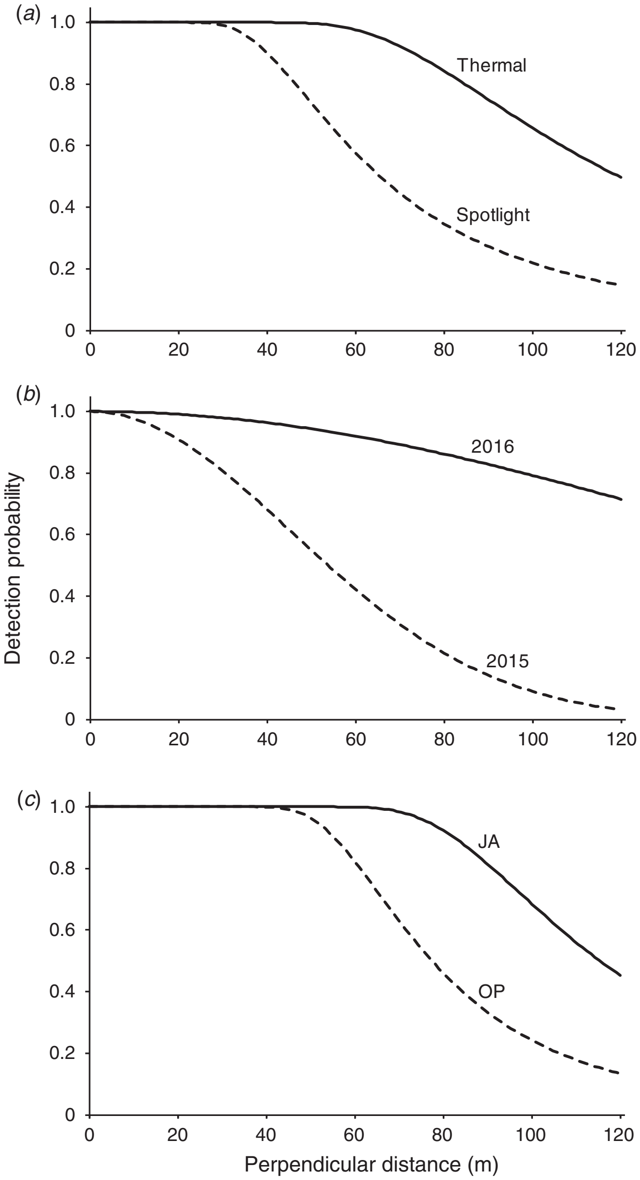

**Fig. 7.** Fitted detection functions for (*a*) spotlight (dashed line) and thermal (solid line) methods using 2015–16 data on the Mooradonka and Kite Drive transects and Model 7 in Table 3 (i.e. the two levels of the covariate METHOD with other covariates ignored); (*b*) 2015 (dashed line) and 2016 (solid line) using 2015–16 data on the Mooradonka and Kite Drive transects and Model 5 in Table 3 (i.e. the two levels of the covariate YEAR with other covariates ignored); and (*c*) observers OP (dashed line) and JA (solid line) using 2015–16 data on the Mooradonka and Kite Drive transects and Model 8 in Table 3 (i.e. the two levels of the covariate OBSERVER with other covariates ignored).

**Table 4. Bilby density estimates (95% CI), truncated sample size (*n*) and detection probabilities (*P* 95%CI) from spotlight and thermal line transect surveys in 2015 and 2016 on the Mooradonka and Kite Drive transects for observers OP and JA**

*P* and density were estimated using Model 2 in Table 3. Total line length (L) for each survey was 82.7 km and truncation distance (w) was 120 m

| Observer | Method | Year | *n* | *P* | Density (95% CI) |
|---|---|---|---|---|---|
| OP | Spotlight | 2015 | 13 | 0.33 (0.20–0.54) | 3.96 (0.98–6.42) |
| JA | Spotlight | 2015 | 14 | 0.49 (0.33–0.74) | 2.86 (0.00–10.42) |
| OP | Spotlight | 2016 | 24 | 0.68 (0.53–0.86) | 3.72 (0.56–5.68) |
| JA | Spotlight | 2016 | 25 | 0.90 (0.78–1.00) | 2.82 (1.58–4.68) |
| OP | Thermal | 2015 | 19 | 0.52 (0.37–0.73) | 3.70 (0.00–8.88) |
| JA | Thermal | 2015 | 21 | 0.74 (0.58–0.94) | 3.00 (0.38–4.62) |
| OP | Thermal | 2016 | 43 | 0.92 (0.84–1.00) | 5.04 (0.92–10.30) |
| JA | Thermal | 2016 | 44 | 1.00 (0.98–1.00) | 4.56 (1.66–8.94) |

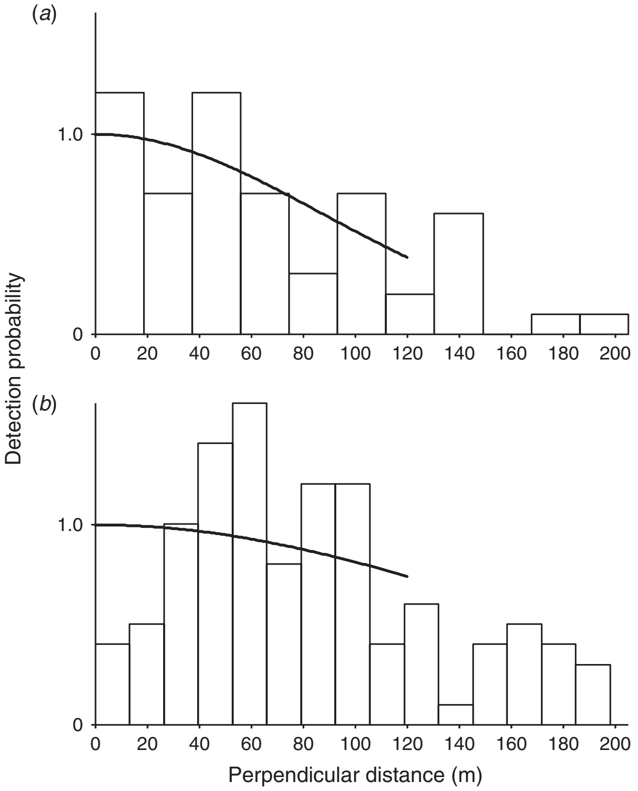

**Fig. 8.** Frequency histogram of bilby clusters sighted in surveys using (*a*) spotlights and (*b*) thermal cameras on the Mooradonka and Kite Drive transects in 2016. The number of sightings is scaled to the *y*-axis. The modelled detection functions (Model 2, Table 3) using data truncated at 120 m are superimposed.

Supplementary material, Appendices S3–S6. Small mammal detection was greater in the thick grassy habitats in comparison to the cracking clay soils. Spotlighting was particularly ineffective in the cracking soils, as small mammals hid in the cracks and were usually detected only if they moved from one crack to another. However, most small mammals typically disappeared down cracks or froze when a spotlight was shone in their direction (behaviour that was observed using a thermal camera), making identification difficult. This freezing response in the small mammals (mostly dunnarts) became apparent only when the thermal cameras were used at the same time as the spotlights.

**Table 5. Density estimates and 95% confidence intervals (CI) for transects surveyed in 2015 and 2016 using thermal cameras**

Densities were estimated using a MCDS model with YEAR and OBSERVER as covariates (N, M, K) or just OBSERVER (N, M, K, C, P). N, Ninu; M, Mooradonka; K, Kite Drive; C, Curica Creek; P, Paraputcheri

| Transects | Density (95% CI) | |
|---|---|---|
| | 2015 | 2016 |
| N, M, K | 3.95 (1.06–7.14) | 5.06 (2.23–8.17) |
| N, M, K, C, P | 2.85 (1.20–6.76) | 3.85[A] |

[A] Extrapolated from the 2015 estimate using rate increase over 2015–16 on the N, M and K transects.

## Discussion

Thermal imaging detected more bilbies and small mammals in general than spotlighting in the current study. This result adds to the increasing amount of evidence that thermal imaging detects a greater proportion of mammal or bird populations than other methods (Boonstra *et al.* 1994; Gill *et al.* 1997; Havens and Sharp 1998; Focardi *et al.* 2001; Corcoran *et al.* 2019; Lethbridge *et al.* 2019). The main advantage of using thermal imaging cameras is the larger sample size that can be obtained in comparison to other methods (Focardi *et al.* 2001) and the accuracy of counts (Ganow *et al.* 2015). Despite the increased number of bilbies detected, the densities derived from the two methods (thermal camera versus spotlight) were surprisingly similar because counts were adjusted by detection probability calculated through line transect sampling. The increased sample size provided by the thermal imaging does, however, allow for more reliable modelling of detection probability and ultimately more accurate population estimates. Our use of thermal cameras to survey bilbies and other wildlife should have broad application, but will need testing elsewhere, including for bilbies in the acacia shrublands and hummock grasslands of the Northern Territory and Western Australia.

Although survey distance data can be pooled across years to generate a detection function, vegetation cover and ultimately detection probability at Astrebla can vary greatly from year to year. Modelling a composite detection function can be difficult and unreliable in a CDS analysis. MCDS can help in situations where sample size is small, as in this study, and CDS analyses that are not robust to pooling (Marques *et al.* 2007). MCDS enabled density to be estimated with small sample sizes on an individual year's survey. YEAR was an important covariate, but a measure of vegetation cover would be a better alternative. It could be a non-factor covariate (i.e. continuous variable), requiring fewer parameters, and could be used with geographic as well as temporal strata.

The 2016 thermal camera data were clumped at 50–70 m, which is problematic. Observers either failed to detect bilbies close to the line or bilbies were moving in response to the vehicle. Thus two assumptions of distance sampling (all animals are detected on the line and animals do not move before detection: Buckland *et al.* 2001), may have been violated. The lack of ground cover in 2016 may have made the bilbies more likely to react to the vehicle noise and headlights by either moving away or retreating to burrows, but this problem was not observed in the spotlighting data. The angle of the cameras meant that animals on the line were not detected immediately. To avoid this problem, it is recommended that a third thermal camera be set up to detect animals on or close to the line, instead of relying on the vehicle's headlights. This would also avoid the possible problem of 'guarding the centreline' (Buckland *et al.* 1993; Marques *et al.* 2007), leading to detection functions that are difficult to model.

The difference in the number of animals detected with each method was greatest in 2014 and 2016, which covered the extremes of vegetation cover. More ground cover made it harder to spotlight animals that were still visible using thermal cameras and less ground cover meant that the thermal cameras were able to detect animals at greater distances than spotlights. The lack of groundcover in 2016 meant that animals were detected further from the vehicle than in previous years. Often animals were observed on the thermal camera screen that could not be seen with a spotlight until they or the vehicle moved closer. Unlike the typical response to a spotlight, animals often did not freeze or retreat underground and could be observed with the thermal camera moving across the landscape, apparently undisturbed.

Because of low numbers of bilbies in 2014, the data had to be pooled with data from 2015 to model detection probability and estimate density. Survey effort would need to increase to estimate such low densities with confidence from a single survey. Estimating these low densities accurately would have been problematic with most techniques. The required degree of accuracy will depend on the management question, such as whether density is below a threshold. The adequacy of the precision reported here will depend, for example, on the percentage change in abundance that conservation managers wish to detect following management intervention. Only large changes would be statistically significant using the transect line length used here and with this bilby dispersion. Bilbies were patchily distributed at the time of the survey and this heterogeneity is reflected in the broad confidence intervals surrounding the density estimates. Although data precision in this study was sufficient to detect an increase in abundance from 2014, confidence intervals could be improved through increasing the line length (Buckland *et al.* 1993) and stratification based on habitat, burrow density or past bilby density.

Thermal detection rates improved as the air temperature decreased and the temperature difference between the landscape and the animals increased. Observer experience in the use of thermal cameras improved the detection of bilbies and small mammals, particularly at greater distances. This resulted in detection probabilities differing between observers. While densities were similar, some training is necessary to avoid missing animals on or near the line and to reduce the need for separate detection functions for observers.

The size of Astrebla and the rough terrain make ground-based surveys of the entire park difficult and time consuming. To estimate density across Astrebla, the relationship between bilby density determined from vehicle surveys and burrow density from aerial counts (using the method of McRae 2004) would need to be determined. An estimate of the proportion of the bilby population that remain in burrows at the time of a survey also needs to be factored into the calculations, as has been done for other burrowing species (e.g. Swann *et al.* 2002; Hounsome *et al.* 2005) and marine mammals (e.g. Bengtson *et al.* 2011) using telemetry. Bilby density across the park could then be more accurately determined through aerial survey. Double sampling (Thompson 1992; McCallum 2000) is an appropriate statistical framework to combine these data.

## Conflicts of interest

The authors declare no conflicts of interest.

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