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Reintroduction of Bilbies *(Macrotis lagotis)* to Matuwa, an Indigenous Protected Area in Western Australia ☆

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ABSTRACT

The greater bilby *(Macrotis lagotis)* once occupied much of Australia's mainland. Bilbies are now listed as vulnerable and only occur in 20% of their former range. *Operation Rangeland Restoration* aims to to restore an ex−pastoral lease; reintroduce several species of locally extirpated fauna, including the bilby; and maintain the area in perpetuity for the conservation of Australian arid zone species. Bilbies were reintroduced to the Matuwa Indigenous Protected Area between 2007 and 2010 and, with ongoing landscape-scale control of feral predators, herbivores, and fire, have thrived. Here, we present a detailed account of the methods used during the reintroduction, showing that between 2007 and 2019 there has been an 88% increase in the area of occupancy by bilbies at Matuwa. The results of 2-ha track plot surveys conducted by the traditional owners of Matuwa suggest that the reintroduced bilbies are emigrating out of Matuwa. In addition, in 2018 and 2019 we used 120 camera-traps over 18 mo and occupancy analysis to confirm the widespread presence of bilbies across Matuwa and define significant habitat correlates. Bilbies were more likely to be detected on sandplains with *Eucalyptus* species as overstorey vegetation and *Triodia* as understorey vegetation. Bilbies were not detected in habitats with ≥ 75% bare ground. We attribute the success of the bilby reintroduction at Matuwa to the consistent implementation of landscape-scale control of feral predators.

Introduction

Since European settlement, Australia's terrestrial mammal fauna has suffered a severe and continued decline (Burbidge et al. 2009; Geyle et al. 2018), and 30 of 273 Australian endemic mammal species have become extinct (Woinarski et al. 2015). Arid zone mammal species within the critical weight range (CWR) of 35 g–5.5 kg have suffered disproportionately in the decline, with up to 50% of species now extinct (McKenzie et al. 2007; Moseby et al. 2009) including two in the past decade (Woinarski et al. 2019).

Mitigating the decline of CWR mammals usually focuses on reducing the threats that endangered them, primarily predation by introduced cats *(Felis catus)* and red foxes *(Vulpes vulpes)*, and competition with introduced herbivores (Finlayson et al. 2008). When threats are sufficiently reduced, species reintroductions may be initiated (Moseby et al. 2011; Parlato and Armstrong 2013; Muths et al. 2014). The primary goal of reintroductions is to reestablish viable, self-sustaining populations in areas where they once occurred. The purpose of this is both restoring some level of local ecosystem function and improving the conservation status of those species (IUCN/SSC 2013; Palmer et al. 2020). Accumulative conservation evidence suggests that species reintroduction projects are typically beneficial for threatened species, particularly in Australia (Mawson 2004; Clayton et al. 2014; Littlewood et al. 2020).

Historically, the greater bilby *(Macrotis lagotis)*, a CWR species that is 0.6–2.5 kg in weight, occupied a large part of arid and semi-arid Australia and at the time of European settlement (Southgate 1990; Moritz et al. 1997; Dziminski et al. 2020, 2021). Bilbies now only occur in approximately 20% of their former range (Southgate et al. 2007) and are listed nationally as vulnerable (EPBC 1999). Wild populations are currently found in the northwest of Western Australia (WA), parts of inland Northern Territory, and an isolated population in southwest Queensland (Southgate 1990;

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Bradley et al. 2015; Cramer et al. 2017; Dziminski et al. 2020). Predation by introduced predators, particularly foxes, is thought to be the primary threat for the bilby, with altered fire regimes and pastoralism being landscape-scale factors also affecting bilby range and prevalence (Cramer et al. 2017).

Western Australia's Department of Biodiversity Conservation and Attractions (DBCA) *Operation Rangeland Restoration* aims to restore an ex–pastoral lease, reintroduce several species of locally extirpated fauna, and maintain the area in perpetuity for the conservation of Australian arid zone species (Morris et al. 2007). Landscape-scale control of threatening processes and habitat restoration are required to achieve these aims. Lorna Glen, a pastoral lease, was purchased in 2000 by the WA government to complement the State's conservation reserve system. In 2015, Lorna Glen became a part of the Matuwa Kurrara Kurrara exclusive possession indigenous protected area (IPA), held in trust by Tarlka Matuwa Piarku Aboriginal Corporation (TMPAC) for the Martu people, and is once again referred to by the traditional name Matuwa (Tran and Langford 2015). Biological and subfossil record surveys predicted that up to 37 nonvolant mammal species once existed on Matuwa with only 20 of those species observed persisting in 2006 (Baynes 2006). Bilbies had not been recorded on Matuwa in historic times, nor were they detected in the subfossil record, but their historical distribution suggests they most likely occurred there in the past (Baynes 2006) with the nearest known natural bilby population being in the Little Sandy Desert 100 km north (Dziminski et al. 2020). They were included in the 11 species of locally extinct mammals to be reintroduced as part of *Operation Rangeland Restoration*.

It is imperative during any reintroduction attempt to make sure that existing threatening processes have been minimized (Moseby et al. 2011) and that sufficient resources are available for translocated animals (Armstrong and Seddon 2008; IUCN/SSC 2013). On Matuwa, domestic cattle were removed and all artificial watering points (bores, dams) were closed in 2000. Sporadic culling programs for transient feral herbivores such as camels *(Camelus dromedarius)* are reinforced by a solar-powered single-wire electric fence along the boundary of Matuwa, installed in 2011, which deters incursions by feral herbivores. Volunteer caretakers inspect this fence every month repairing any breaks as encountered. Annual feral cat control using *Eradicat* baits began in 2004, and the abundance of cats was reduced by approximately 60–70% (Algar et al. 2013; Christensen et al. 2013; Lohr and Algar 2020). A regime of prescribed patch burning was initiated in 2006 (Muller 2006) to increase habitat diversity and restrict the spread of wildfires (Burrows 1991; Penman et al. 2011; Burrows and Butler 2013). After 7 yr of these threat mitigation activities, fewer than 10 feral cats were being detected per 100 km of linear transect (Algar et al. 2013) and bilbies were reintroduced to Matuwa.

Despite the threat mitigation activities that were implemented, population viability analyses (PVA) of the Matuwa bilby population using data collected from animals translocated in 2007–2010 and the software VORTEX predicted that the probability of extinction for the Matuwa bilby population after 20 yr was 56.8% with an ongoing negative stochastic growth rate ($r = -0.108$), unless the adult mortality rate of bilbies could be reduced from the 56% measured in the field to 16%, which would reverse the predicted trend (Pertuisel 2010). While the demographic parameters used in this PVA were derived from animals recently translocated to Matuwa, and should be treated with caution, other PVA models have also suggested that a reintroduction program was unlikely to result in a self-sustaining population of free-roaming bilbies (Southgate and Possingham 1995). With such a grim outlook, ongoing monitoring of the bilby population at Matuwa was prioritized.

Since 2015, the Matuwa Kurrara Kurrara Rangers have been using repeated surveys of 12–20 two-ha track-plots to monitor the persistence of bilbies at Matuwa. Their data revealed ongoing persistence of the species, but the sample size was too small for formal ecological analyses. Fecal DNA-based abundance monitoring on a relatively small section of Matuwa in 2016 revealed that within 9 yr the bilby population at Matuwa had increased sevenfold to at least 971 ± 258 (SE) individuals from the original 144 founders in 2007–2010 (Dziminski et al. 2021). The results of these studies contradict the expectations of the PVA.

In 2018, we decided to use camera-traps and occupancy modeling to monitor the bilby population across the entirety of Matuwa with the intent to confirm their ongoing presence, document population expansion and changes in extent of occurrence over time, and define any correlations between bilby presence and habitat type. On the basis of prior studies at Matuwa (Chapman 2013) and in the Tanami desert (Southgate et al. 2007), we expected that bilby occupancy rates would be higher in spinifex (*Triodia* sp., hummock grasses) sandplain habitats over mulga (*Acacia* sp.) stony plain habitats. In addition, we expected bilby occupancy rates to negatively correlate with the percentage of bare ground, as vegetation provides escape cover against predation (Gotceitas and Colgan 1989; Kazantzidis and Goutner 1996).

Methods

Study Site

Matuwa (244 000 ha) lies in central Western Australia (−26.1986; 121.3598) and straddles the Murchison and Gascoyne Interim Biogeographic Regionalisation for Australia (IBRA) regions (Department of Agriculture Water and the Environment 2020). It contains at least 20 different land systems and vegetation types such as hummock grasslands, shrublands, or low woodland with mulga (e.g., *Acacia aneura*). This diverse habitat supports a remarkable array of flora and fauna, with 480 vascular plant species and 220 vertebrate species occurring on the property (Department of the Environment Water Heritage and the Arts 2009; Rabosky et al. 2011). The extant diversity of small vertebrates is one of the highest recorded in Australia, with records of at least 75 reptiles, 5 frogs, 133 birds, 4 bats, 9 dasyurids, and 4 rodent species (Baynes 2006; Coate 2010; Chapman and Burrows 2015). Matuwa has an arid climate with an average monthly temperature of 30°C in summer and 13°C in winter. The mean annual rainfall is 262 mm (Bureau of Meterology Station 13005), which primarily occurs in the summer months due to remnant tropical low-pressure systems. As expected, little rain (1.2–16.4 mm) fell during the month of the translocations and yr 2007, 2008, and 2010 experienced near mean rainfall, whereas 2009 was dry with only 167.7 mm of rainfall (Table 1).

Source Populations

Bilbies reintroduced to Matuwa were sourced from three sites. The numbers of bilbies taken from each source site is shown in Table 1.

The Peron Captive Breeding Center (PCBC) in Shark Bay, Western Australia, which operated from 1996 to 2013, was an intensive native animal breeding facility located in the Carnarvon IBRA region that used small mesh-covered pens, as well as larger outdoor pens, to accommodate breeding pairs or small family groups (Morris et al. 2004). The Carnarvon bioregion has a semiarid to arid climate with an average monthly temperature of 33°C in summer and 24°C in winter, predominantly winter rainfall (~208 mm annually) and a low and gently undulating landscape with *Acacia* sp. shrublands, saltbush (*Atriplex* sp.) shrublands, and areas of tussock grassland in the north. PCBC had the most similar climate and vegetation type to Matuwa.

Table 1
Number of bilbies translocated to Matuwa, their origin, and number of tracked individuals lost to 4 causes of mortality.

Origin	Date	Monthly rainfall (annual rainfall) mm at Matuwa[1]	No. males	No. females	Total	Release site	No. (%) tracked[2]	No. (%) mortality of tracked individuals			
								Cat	Other predation	Starvation	Unknown
RTD	Aug 2007	NA (> 296.9)	14	11	25	12*Ninu 3[2] 13*Ninu 2	13 (52)	4 (31)	4 (31)	0 (0)	1 (8)
PCBC	Aug 2007		10	5	15	Ninu 3[2]	11 (73)	2 (13)	1 (8)	3 (20)	1 (8)
PCBC	Oct 2007	1.2 (> 296.9)	2	4	6	3*Ninu 1 3*Ninu 2	4 (66)				
Thistle Is.	Aug 2008	16.4 (259.3)	17	15	32	6*Possum Lake 5*Pink Lake 10*North well 10*Gidgee Bore	14 (44)	2 (14)	0 (0)	6 (19)	2 (14)
RTD	Aug 2008		16	11	27	Ninu 1	10 (37)	6 (26)	1 (4)	0 (0)	4 (17)
PCBC	Sept 2008	2.1 (259.3)	0	1	1	Possum Lake	0 (0)	–	–	–	–
RTD	Aug 2009	2.6 (167.7)	13	0	13	6*Pink Lake 5*Possum Lake 2*North Calamity	0 (0)	–	–	–	–
PCBC	Aug 2009		6	5	11	10*Ninu 1 1*Possum Lake	0 (0)	–	–	–	–
PCBC	July 2010	14.0 (236.0)	11	3	14	Possum Lake	4 (28)	–	–	–	–
Total		Mean = 262 mm	89	55	144		56	14	6	9	8

RTD indicates return to Dryandra captive breeding facility; PCBC, Peron Captive Breeding Centre; Thistle Is., Thistle Island, South Australia.

[1] Rainfall statistics from Bureau of Meterology Lorna Glen Station 13005.

[2] Three of these individuals were recaptured and moved to Ninu 1 in October 2007 due to a high rate of cat predation.

The Return to Dryandra (RTD) facility is a low-intensity breeding facility that opened in 1998. It consists of two 10-ha pens, with animals of several species kept simultaneously (Friend and Beecham 2004). RTD is located in the Avon Wheatbelt bioregion and is characterized by a dry Mediterranean climate, with an average monthly temperature of 30°C in summer and 15°C in winter. Average rainfall ranges from 325 to 700 mm along an east-west axis and predominately falls during winter. RTD has a gently undulating landscape, with mixed eucalypt, *Allocasuarina* sp. woodlands and proteaceous scrub-heaths, and is rich in endemic plant species (Bamford et al. 2009).

Thistle Island, South Australia, is a 3 926-ha island in the Eyre York Block bioregion. It has a temperate climate with warm summers (average temperature 21°C) and cool winters (average temperature 12°C) and an annual rainfall up to 600 mm, most of which occurs in winter. The vegetation consists mostly of mallee woodlands and shrublands with areas of eucalypt woodlands and chenopod and samphire shrublands, *Callitris* woodlands, *Melaleuca* shrublands, and tussock grasslands. Bilbies were translocated from Thistle Island to Matuwa in 2008 (Berris et al. 2020).

Bilbies in the PCBC and RTD facilities were originally sourced from the Kimberley and Pilbara regions of Western Australia. The bilbies on Thistle Island originated from the captive breeding program at the Monarto Safari Park in South Australia (Berris et al. 2019). Founding animals in the Monarto captive breeding program were sourced from wild populations in Western Australia and the Northern Territory (Moseby and O'Donnell 2003). Ultimately, the founders of the bilby population at Matuwa represented all the known wild populations of bilbies at that time, except the population in southwestern Queensland.

Reintroduction Sites

In 2007, three sites on Matuwa (Ninu 1-3) were identified as potential release sites for the bilbies (Morris et al. 2008). These three sites were selected initially because they matched the apparent habitat requirements of bilbies and the sites were easily accessible, near base camp, and had been subject to feral cat baiting.

Ninu 1 (Fig. 1) is on the Lorna land system (Mabbutt 1963) and consists of sandy loam with mulga and Eucalypt shrubland over diverse understorey vegetation. By 2007, Ninu 1 had been subjected to 4 yr of feral cat baiting with *Eradicat* (Algar et al. 2013). Ninu 2, located in the Bullimore land system, consisted of deep red sands with *Acacia grasbyi* and *Eucalyptus* species over *Triodia* and was adjacent to a site selected by traditional owners. Ninu 3 was also located in the Bullimore land system but was adjacent to a sand dune. Ninu 2 and 3 were not baited with *Eradicat* until June 2007, two mo before the first translocation. The feral cat track-activity index in unbaited sites at Matuwa typically counted 15–35 cats per 100 km of 4WD track surveyed, whereas sites with annual baiting programs typically counted fewer than 10 cats per 100 km (Algar et al. 2013).

A total of 144 bilbies with a male-biased sex ratio (1.6:1) were released at Matuwa between August 2007 and July 2010. Twenty-seven (19%) out of 46 released in 2007 were released at site Ninu 3 (see Table 1; Fig. 1). Subsequently, six of these animals were recaptured and moved to site Ninu 1 in October 2007 due to a high rate of predation. Sixty bilbies were released in 2008, 24 were released in 2009 (Miller et al. 2010), and 14 were released in 2010. Some 38% of the released bilbies were radiotracked using tail-mounted radiotransmitters described by Moseby and O'Donnell (2003).

Bilbies released in 2007 were released into 40 artificial burrows spaced 200 m apart consisting of 1-m length of straight polyvinylchloride pipe, 200 mm in diameter, with a 150-mm-wide longitudinal section removed, buried at an approximately 20-degree downward angle (see supplemental file, available online

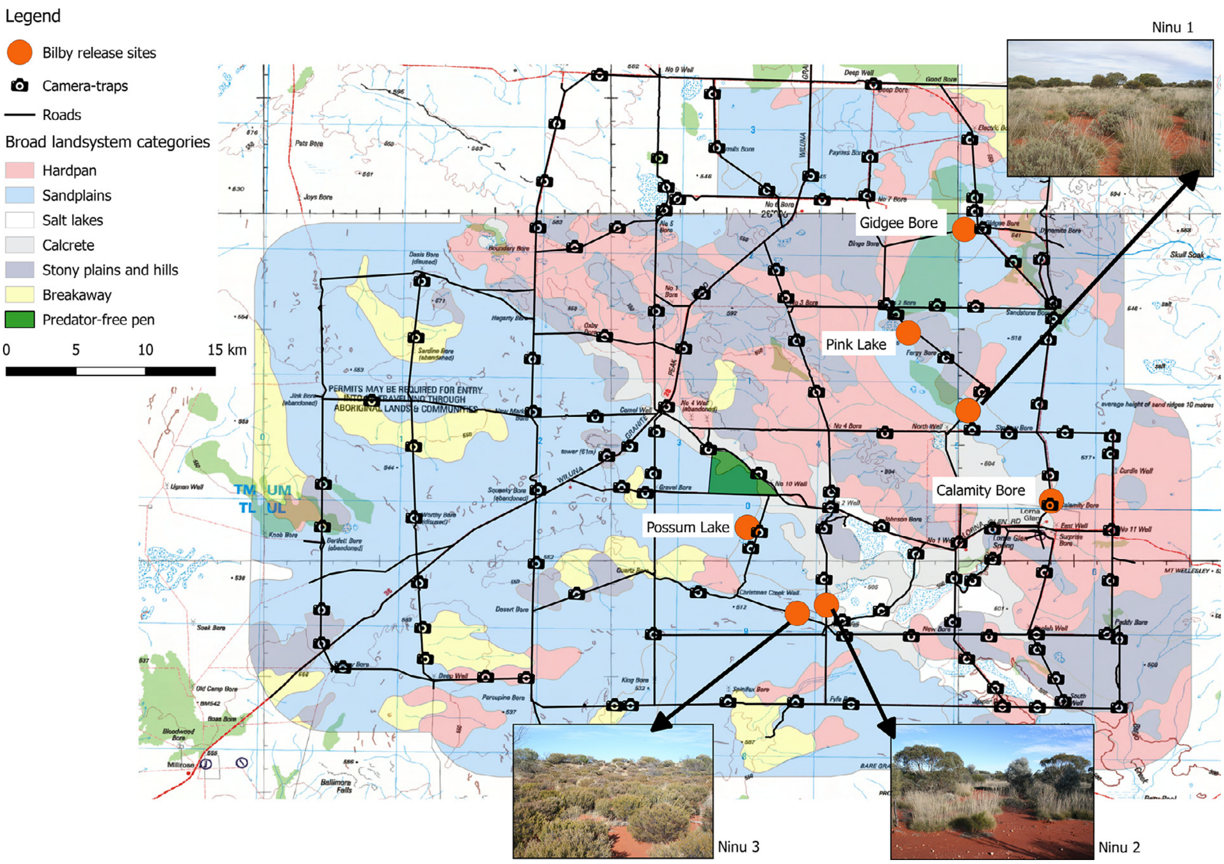

Figure 1. Map of the Matuwa Indigenous Protected Area with release sites for translocated bilbies, location of 120 camera-traps used for occupancy analysis, and six broad landsystem categories. Insert photographs depict the original three release sites used in 2007.

at …). These pipes were dug into sandy substrate at the release site Ninu 3 (see Fig. 1), creating an artifical burrow with a sandy floor and supported roof. Bilbies released in subsequent years were released into preexisting natural burrows. No bilbies were released in the predator proof enclosure, which was built in 2009–2010 (Bode et al. 2012).

Radiotracking

Radiotracking was used to monitor the survivorship, refuge use, and movements of the released animals in the first 3–6 mo following the reintroductions (Miller et al. 2010; Pertuisel 2010). For each release, a proportion of the bilbies were fitted with a tail-mounted radiotransmitter (Moseby and O'Donnell 2003) from Sirtrack, Havelock North, New Zealand with a 4-mo battery life and mortality mode latched after 6 h of inactivity (see Table 1). Daily radiotracking from the ground was conducted over 98 d following the first release (between August and November 2007), using handheld Yagi antennas (detection range of 500 m) and a vehicle-mounted aerial device (detection range of 1 000 m). Much of the radiotracking was only used to monitor survivorship through mortality signals. As often as possible, personnel tracked bilbies back to their burrow. After the second release in 2008, bilbies fitted with radiotransmitters were daily radiotracked over 87 d (August–November). Radiotracking continued opportunistically beyond these periods when experienced personnel were available.

We estimated the minimum convex polygon (MCP) and 95%, 75%, and 50% fixed kernal density estimator for bilbies with at least 10 confirmed diurnal refuges using the software Biotas (Ecological Software Solutions 2021). No fixes were excluded from the dataset, and we included the site of release as we intended to estimate the post-translocation movement of bilbies released on the open landscape. Unfortunately, we could not obtain sufficient points ($n \geq 50$; (Seaman et al. 1999) for an unbiased estimate of stable home-range; hence, our results may overestimate the area used by translocated bilbies and should be interpreted as the potential post-translocation movement of bilbies released on the open landscape.

Extent of Occurrence and Area of Occupancy

Bilby records were sourced from the DBCA NatureMap database (Department of Biodiversity Conservation and Attractions 2019); the 2016 fecal DNA abundance monitoring (Dziminski et al. 2020); surveys of 2-ha track plots located on Matuwa, Kurrara Kurrara IPA (22–65 km to northeast), and the Jundee pastoral lease (55–80 km west), held by Northern Star Resources Limited; opportunistic data from previous DBCA surveys; and camera data from this study. Track plots were surveyed by the Wiluna or Matuwa Kurrara Kurrara Aboriginal Ranger teams with a total of 58 plots surveyed in 2014 (Matuwa = 28, Jundee = 30), 70 plots in 2015 (Matuwa = 34, Jundee = 36), 67 plots in 2016 (Matuwa = 30, Jundee = 24, Kurrara Kurrara = 13), and 26, 63, and 72 plots surveyed on Matuwa only in 2017, 2018, and 2019. Extent of occurrence (EOO) was generated for four time intervals (2007–2010, 2011–2013, 2014–2016, and 2017–2019) by applying a convex hull (Red List Technical Working Group 2018; Atlas of Living Australia website 2019; IUCN 2019) for each time interval. The area within the EOO represented the area of occupancy.

Table 2
Covariates used to model occupancy and detection probabilities for bilbies at Matuwa.

Symbol	Parameter	Description	Categories
LS	Landsystems		Breakaway Calcrete Hardpan Saltlake Sandplain Stony plains
B	Percentage bare ground	Visually estimated percentage of ground with no leaf litter or vegetation within 30-m radius of camera-trap	Continuous
U	Upper storey	Dominant vegetation type > 3 m height	*Eucalyptus* species Mulga or other *Acacia* species *Melaleuca* or *Casuarina* species No vegetation
M	Midstorey	Density of vegetation 1-3 m height	No vegetation Sparse shrubs ($< 10\%$ cover) Mid-dense shrubs (30-70% cover) Dense shrubs ($> 70\%$ cover)
L	Lower storey	Dominant vegetation < 1 m height	Hummock grasses Mixed grasses Tussock grasses Mixed shrubs No vegetation
SURVEY	Survey period	Camera-trap data collated into 4-wk survey periods	23 survey periods in total

Occupancy Analysis

In 2018, 120 camera-traps (Reconyx PC900 Hyperfire Professional Covert camera; Reconyx, Holmen WI) were installed at Matuwa using a stratified-random design based on the 20 most common geological types in the Wiluna region (Farrell 1999). The cameras were placed between 30 m and 200 m off a 4WD drive track, mounted on a 30-cm high plastic sand peg, facing south, in a space with at least 3 m of open ground in front of the camera. Herbaceous vegetation was removed, if present, immediately in front of the camera. Camera-traps were programmed to capture three photos after detecting movement, with no quiet period. Timed photos were also taken at 11:00 and 23:00 h to monitor the quality of photos and operation of the camera. Three cameras were moved in June 2018 by 100 m, 2 km, and 9 km to prevent damage from flood waters, increase the distance between camera-traps, and allow easier access, respectively. Ultimately, camera-traps were on average 2.80 km from their nearest neighbor (min = 0.97 km, max = 5.92 km). Photos were taken between 15 March 2018 and 17 October 2019. Any cameras that malfunctioned were replaced, and the incomplete survey periods were removed from the occupancy dataset before analysis.

Photos were stored in the Colorado Parks and Wildlife Photo Warehouse database (CPW) (Ivan and Newkirk 2016). All photos of bilbies and rabbits *(Oryctolagus cuniculus)*, a potentially misidentified species, were viewed by at least two observers to confirm species identification. Photos of bilbies were used to generate monthly occupancy data for 21 mo (mo = 4 wk).

For analysis of occupancy data, we used the package RPresence (MacKenzie and Hines 2018) in RStudio version 1.2.5033 running R version 3.6.2 (R Core Team 2018). We fit candidate models meant to reflect hypotheses regarding the effects of land systems (Mabbutt 1963), or localized vegetation type and percentage of bare ground on occupancy and detection probability (Table 2). In September 2018, the end of the dry season, we collected data on localized vegetation type in accordance with the Australian National Vegetation Information System, major vegetation subgroups version 5.1 (Department of Agriculture Water and the Environment 2018), and visually estimated the percentage of bare ground to the nearest 5% (or nearest percent if $< 5\%$) within 30 m of each camera-trap.

Bilbies that are not constrained by fences may exhibit large movements and occupy large home ranges (Table 3), whereas camera-traps have a maximum detection range of 30 m. Bilbies migrate to follow food resources, especially in less productive parts of their range (Southgate et al. 2007; Southgate and Carthew 2008). Therefore, bilbies may appear to move randomly in and out of a survey area monitored by camera-traps, and the occupancy estimate should be interpreted as the probability that a bilby will use a given area (MacKenzie et al. 2017).

Broad categories of vegetation type were created for the upper-storey, midstorey, and lower-storey vegetation (see Table 2). Species diversity in the midstorey was highly variable, and hence vegetation categories were based on broad categories of structure. We tested model fit with 5 000 parameter bootstraps on the global model [ψ(LS+B+U+M+L) p(t+LS+B+U+M+L $X^2 = 1.54^6$, $p = 0.99$, $\hat{C} = 0$] and found that a complex model was not overdispersed (MacKenzie and Bailey 2004; MacKenzie et al. 2017). Models with convergence issues or error estimating the covariance matrix were removed from the final model set. Remaining candidate models were compared via Akaike's Informatic Criteron (AIC). To ensure the best model accounted for sufficient heterogeneity and minimize bias in occupancy estimates, we averaged models with ΔAIC < 10. Average estimates of occupancy and detection were plotted against the original covariates (see Table 2).

Results

Translocation and Radiotracking

Ultimately, 1 520 bilby detections were collected at Matuwa through either translocation events, radiotracking, trapping, or mortality events. Of these data, 737 were approximate locations recorded during survivorship monitoring and 783 were confirmed locations for 124 unique bilbies. Eighty-five of those bilbies were only seen once, on the day they were released, whereas 26 bilbies (15 females, 11 males) were located between 10 and 42 times (mean = 20) with a total 490 data points that could be spatially analyzed. These 26 bilbies were tracked to their burrow, which does not provide data on habitat used while foraging. Tracking to repeatedly used, distinct locations also creates wide divergence between estimates of MCP and kernal home ranges.

Table 3
Short-term post-translocation movement range for 26 bilbies translocated to the open landscape at Matuwa, Western Australia, as estimated by at least 10 located diurnal refuges, minimum convex polygon (MCP), and 95%, 75%, or 50% kernal home-range.

Group	Sample size	Method	Average area km^2	Standard deviation area km^2	Minimum area km^2	Maximum area km^2
All	26	MCP	98.8	116.7	0	472.9
		95% kernal home-range	27.3	29.3	7.6	114.5
		75% kernal home-range	8.4	10.2	2.6	42.3
		50% kernal home-range	3.2	3.5	1.1	15.6
Female	15	MCP	38.3	58.3	0	209.1
		95% kernal home-range	18.1	24.3	7.6	108.3
		75% kernal home-range	6.5	9.3	2.6	41.3
		50% kernal home-range	2.4	2.9	1.1	13.2
Male	11	MCP	181.4	125.4	5.1	472.9
		95% kernal home-range	39.9	30.9	13.2	114.5
		75% kernal home-range	10.9	10.7	3	42.3
		50% kernal home-range	4.2	4	1.2	15.6

Tracking data revealed that, although unusual (Moseby and O'Donnell 2003), up to four bilbies would occupy a burrow simultaneously (1 male and 3 females). The MCP and 95% kernal home range for these 26 bilbies suggests that the post-translocation movement range is on average 98.8 km^2 to 27.3 km^2, respectively (see Table 3). The average female post-translocation movement range was approximately one fifth to one half the size of male post-translocation movement range. The average distance from MCP centroid to each bilby burrow was 7.1 km (standard deviation 5.5 km). In comparison, the radiotransmitters fitted to these bilbies could only be reliably detected over 1 km, which likely caused our inability to track 68% of the bilbies with transmitters.

Unfortunately, 37 of the 52 tracked bilbies died. The cause of mortality varied among the source populations. None of the bilbies from RTD died of starvation, which was defined as a lack of fatty tissue observed during necropsy, whereas approximately 20% of the animals from PCBC and Thistle Island suffered from a lack of food resources (see Table 1). Nearly twice as many RTD bilbies were lost to cat predation (28.5%) than bilbies from PCBC (13%) or Thistle Island (14%).

Extent of Occurrence and Area of Occupancy

The number of data points that were used to calculate the EOO for four time intervals (2007–2010, 2011–2013, 2014–2016, and 2017–2019) was 276, 109, 970, and 580, respectively. The area of occupancy (AOO) was 100 047 ha in the 4 yr post reintroduction (Fig. 2). The EOO and AOO decreased in the next 4-yr period (2011–2013) before increasing to an AOO of 188 376 ha in 2017–2019 (see Fig. 2). In addition, two observations were confirmed far to the west in 2015 and 2017. These points were a minimum of 100 km south of the current wild range of the nearest known natural bilby population in the Little Sandy Desert (Dziminski et al. 2020) and are more likely attributable to individuals expanding out of Matuwa, 50 km to the east.

Occupancy Analysis

Occupancy was consistent across our five best models at 0.32 (95% CI 0.21–0.46) with limited variation in respose to the percentage of bare ground, upper-storey vegetation, and landsystem category (Table 4).

The probability of detection, however, varied with upper (Fig. 3) and lower storey (Fig. 4), vegetation type, and landsystem (Fig. 5). The probability of detection was highest in areas with *Eucalyptus* species, hummock grasslands, or sandy soils. Bilbies were less likely to be detected in tussock or mixed grasslands. Similarly, bilbies were less likely to be detected in mulga on stony or hardpan soils or on ephemeral saltlakes. The percentage of bare ground weakly influenced the probability of occupancy, appearing in the sixth strongest model (delta AIC = 17.02; see Table 4), with occupancy declining as the amount of bare ground increased (Fig. 6). Referring to landscape-scale vegetation mapping at Matuwa plus a 5-km buffer (Beard et al. 2013), hummock grasslands cover an area approximately 1 325 km^2 (Table 5), whereas the other vegetation associations cover a combined area of 2 275 km^2.

Discussion

Bilbies are still surviving at Matuwa without predator-proof fencing 13 yr after reintroduction. Bilbies currently occupy large areas of Matuwa, their abundance has increased significantly (Dziminski et al. 2020), and there is evidence of them expanding outside the IPA. While bilby occupancy did not vary with habitat as hypothesized, bilby detection rates were higher on sandplains with hummock grasses. Bilbies were less likely to use sparesly vegetated areas with stony or hardpan soils, tussock grasses, or mulga or melaleuca overstorey.

The success of reintroducing bilbies without predator-proof fencing appears to hinge on the success of landscape-scale control of feral cats and other introduced predators. Within a fenced reserve, bilby populations have been shown to be able to survive and increase in the presence of 0.46 cats/km^2 (Moseby et al. 2019). At Matuwa we consistently suppress the abundance of feral cats using aerial baiting (Lohr and Algar 2020). Matuwa remains the only location in Australia with a successfully reintroduced population of bilbies on an open (i.e., not fenced or an island) landscape (Moseby and O'Donnell 2003; Berris et al. 2020; Lott et al. 2020). This research does not, however, investigate any direct causal relationships between the abundance of feral cats and presence of bilbies. The application of landscape-scale habitat rehabilitation activities, especially landscape-scale fire mosaics that inhibit large and severe wildfires that reduce fire-age heterogeneity (Southgate et al. 2007), has likely assisted the establishment of bilbies.

In 2013 and 2019 we demonstrated that we were able to suppress the population of feral cats at Matuwa to 10 cat detections per 100 km transect using toxic baits (Algar et al. 2013; Lohr and Algar 2020). If we assume that the track activity index for feral cats detects all cats within 100 m of the track, then the 100-km transect is congruent to a survey of 20 km^2 and 10 cats/100 km is not dissimilar to 0.46 cats/km^2. The first release site, Ninu 3 (see Fig. 1), was selected in 2007 and had only been baited once with *Eradicat* 2 mo before the translocation. Twenty-seven bilbies were released at the site, of which 31% were lost to cat predation (see Table 1). Six of those bilbies were recaptured and moved to a site that had been subject to 4 yr of annual feral cat control.

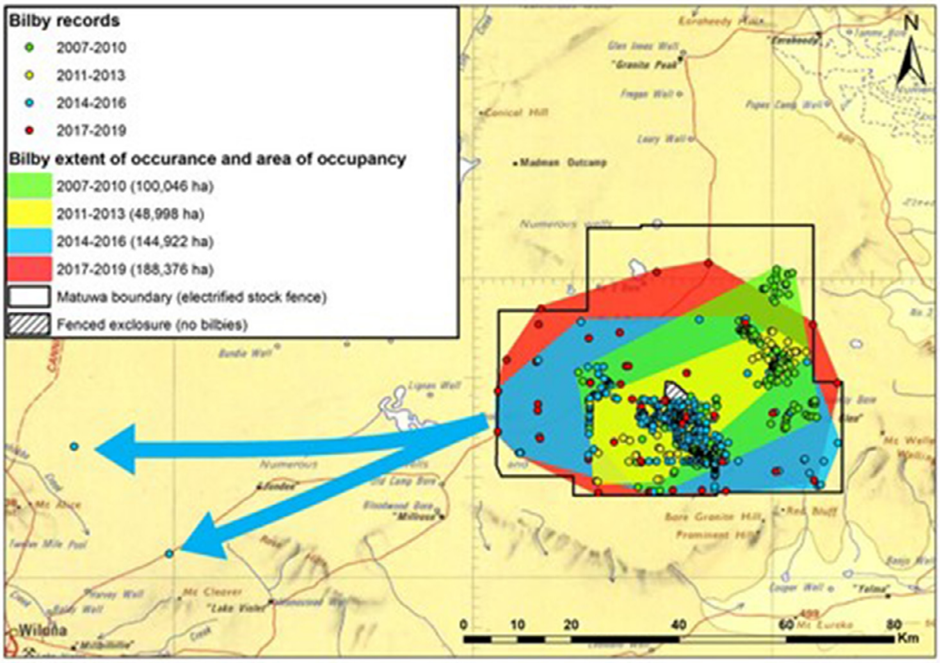

Figure 2. The extent of occurrence and area of occupancy estimated for bilby (*Macrotis lagotis*) population on the Matuwa Indigenous Protected Area between 2007 and 2019. The predator-free fenced reserve was completed in 2011 with no bilbies inside the fence. The western-most point was recorded in 2015, and the south-western point was recorded in 2017.

Table 4
Candidate bilby occupancy models compared using Akaike's Information Criterion.

Model no.	Model	AIC	ΔAIC	K	LL	Weight	psi (95% CI)	
mod41	psi (.) p (U)	544.32	0	5	1	0.53	0.31 (0.21-0.44)	
mod46	psi (.) p (L)	544.76	0.44	6	0.80	0.43	0.33 (0.23-0.46)	
mod43	psi (.) p (U + SURVEY)	549.89	5.56	25	0.06	0.03	0.31 (0.21-0.44)	
mod10	psi (.) p (LS)	552.03	7.71	7	0.02	0.01	0.31 (0.22-0.43)	
mod45	psi (.) p (LS + SURVEY)	557.71	13.39	27	1.00^{-3}	7.00^{-4}	0.31 (0.22-0.42)	
mod15	psi (B) p (LS)	561.34	17.02	24	2.00^{-4}	1.00^{-4}	See Figure 5	
mod1	psi (.) p (.)	563.71	19.39	2	1.00^{-4}	0	0.26 (0.18-0.35)	
mod3	psi (LS) p (.)	566.98	22.66	7	0	0	Breakaway	0.19 (0.02-0.68)
							Calcrete	0.40 (0.15-0.71)
							Hardpan	0.15 (0.05-0.38)
							Saltlake	0 (0-0)
							Sandplain	0.29 (0.18-0.44)
							Stony	0.30 (0.14-0.53)
mod34	psi (U) p (.)	567.01	22.69	5	0	0	Mulga	0.22 (0.14-0.33)
							Melaleuca	0.15 (0.02-0.60)
							None	0.32 (0.11-0.66)
							Eucalyptus	0.40 (0.19-0.64)
mod4	psi (.) p (SURVEY)	570.42	26.10	22	0	0	0.25 (0.18-0.34)	
mod39	psi (B) p (.)	570.51	26.19	19	0	0	See mod15	
mod30	psi (U + B) p (.)	572.03	27.71	22	0	0	See mod34 and mod15	
mod27	psi (U) p (SURVEY)	573.73	29.41	25	0	0	See mod34	
mod16	psi (B + LS) p (.)	576.23	31.91	24	0	0	See mod15 and mod3	

psi indicates probability of occupancy; p, detection probability with; '.', constant; K, number of parameters; LL, log-likelihood.

Subsequent releases in 2008–2010 after additional applications of *Eradicat* recorded lower levels of mortalilty due to predation. Our research provides anecdotal evidence that supports the results of Moseby et al. (2019), suggesting that intensive feral cat control with multiple control methodologies should be a priority on sites with bilbies.

Toxic baiting is recognized as the most effective method for managing feral cats at a landscape-scale in Australia (Short et al. 1997; Algar and Burrows 2004; Algar et al. 2007, 2013; Richards 2012; Lohr and Algar 2020). In Western Australia the poison bait, known as *Eradicat,* which contains 4.5 mg of "1080" (sodium monofluoroacetate), is applied annually at a rate of 50 baits/km^2 for the control of feral cats (Algar and Burrows 2004; Algar et al. 2007). *Eradicat* baits are distributed across the entirety of the property during the cool, dry winter periods (Algar and Burrows 2004) when the abundance and activity of all prey types and ants are low.

Contrary to the predictions made by Pertuisel (2010), the EOO and AOO have expanded and the abundance of bilbies has increased (Dziminski et al. 2021) at Matuwa. Pertuisel (2010) made several incorrect assumptions during the definition of the parameters for the population viability analysis (PVA). First, she assumed a male-biased sex ratio at birth because the population of adult animals reintroduced to Matuwa was male biased (1.5:1). Other authors have stated that bilbies have a 1:1 sex ratio at birth (McCracken 1990). Using a male-biased sex ratio at birth will re-

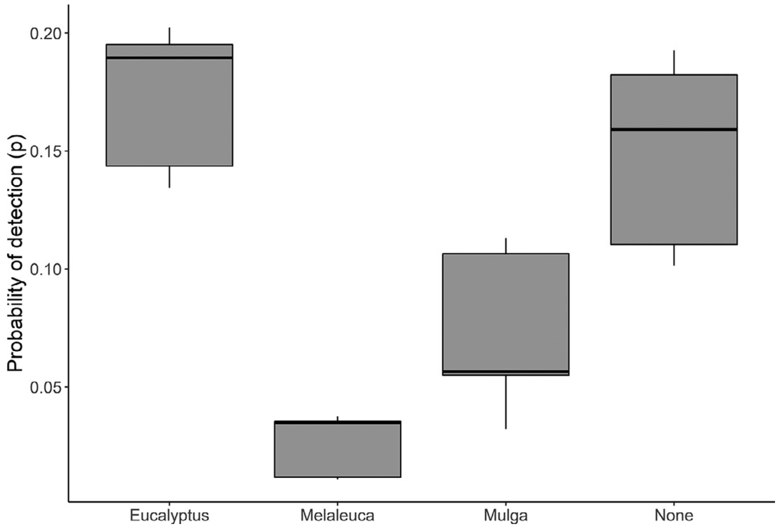

Figure 3. Variation in the probability of detection of bilbies with dominant vegetation in the upper storey as predicted by the averaged model.

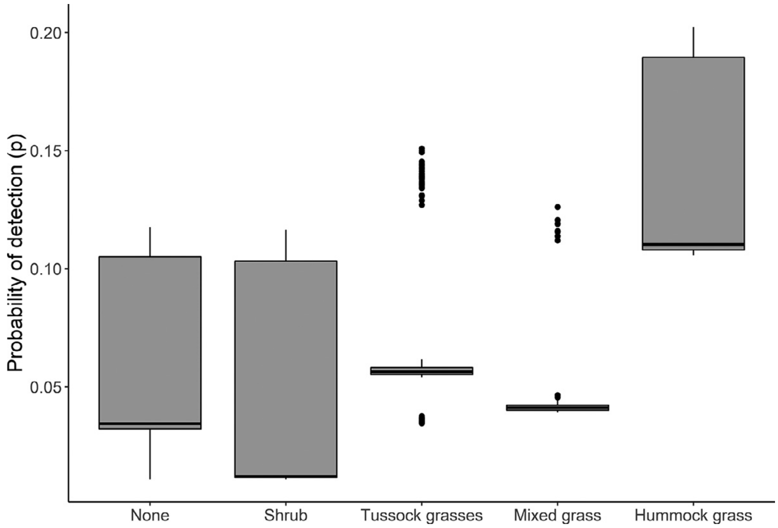

Figure 4. Variation in the probability of detection of bilbies with dominant vegetation in the lower storey as predicted by the averaged model.

Table 5

Area covered by landscape-scale vegetation types[1] on the Matuwa Indigenous Protected Area plus a 5-km property buffer.

Vegetation formation	Structural description	Floristic description	Area (km^2)
Spinifex grassland	Shrub-steppe	Hummock grassland with scattered shrubs or mallee *Triodia* spp., *Acacia* spp., *Grevillea* spp., *Eucalyptus* spp.	1325.38
Halophyll and sarcophyll communities	Samphire with scattered medium or low trees	York gum, mulga, melaleuca or casuarina *Tecticornia* spp., *Eucalyptus loxophleba, Acacia aneura, Melaleuca* spp., *Allocasuarina* spp.	106.05
Halophyll and sarcophyll communities	Saltbush and bluebush with scrub or open scrub	Mulga, other wattle *Atriplex* spp., *Maireana* spp. with *Acacia aneura* & other *Acacia* spp.	88.31
Low forest and woodland (< 10 m tall)	Low woodland, open low woodland, or sparse woodland	Mulga *Acacia aneura* and associated species	1582.13
Tall (sclerophyll) shrubland (> 1 m tall)	Scrub, open scrub or sparse scrub	Wattle, teatree, & other species *Acacia* spp., *Melaleuca* spp.	310.99
Halophyll and sarcophyll communities	Samphire with thicket/scrub	*Tecticornia* spp. with *Melaleuca* spp., *Acacia* spp.	4.24
Halophyll and sarcophyll communities	Samphire	*Tecticornia* spp. communities in saline areas	155.55
Bare areas	Salt lake, lagoon, clay pan		28.01

[1] Vegetation types defined by Beard et al. (2013).

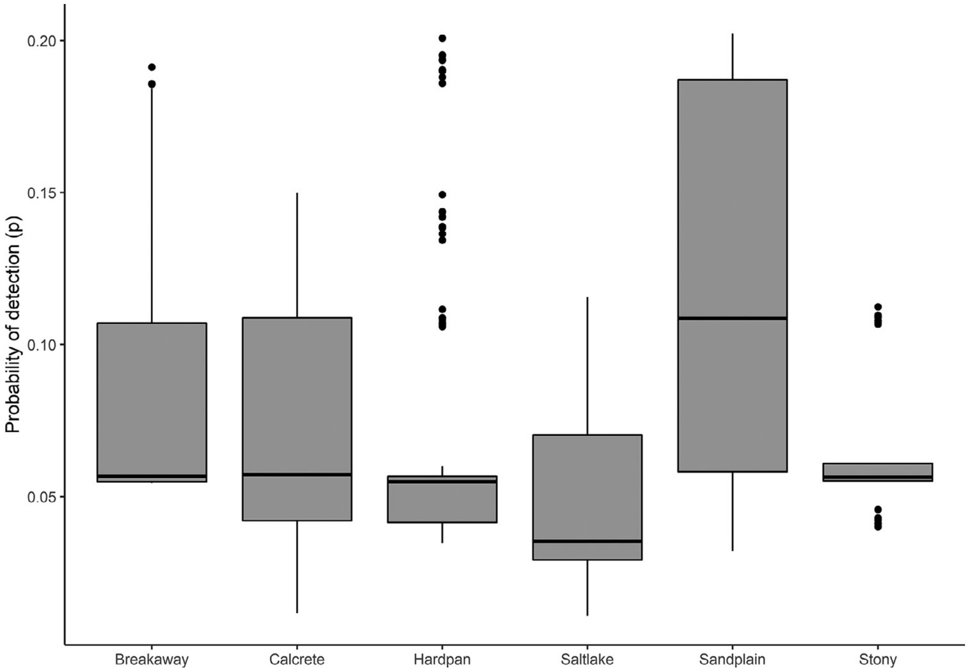

Figure 5. Variation in the probability of detection of bilbies with landsystem as predicted by the averaged model.

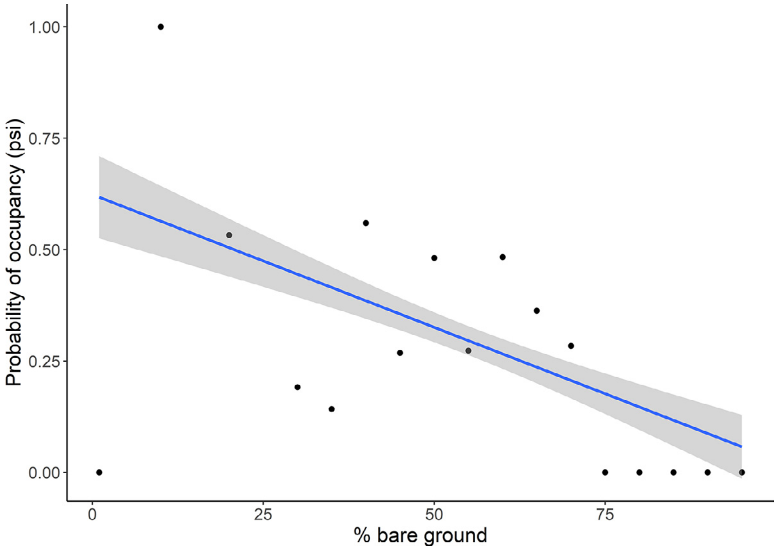

Figure 6. Variation in the probability of occupancy of bilbies against the percentage of bare ground as predicted by the sixth best model (delta AIC = 17.02 ; Table 4): psi (B) p (LS).

duce the predicted mean time to extinction and increase the predicted probability of extinction (Ferrer et al. 2009).

Second, the annual mortality of adults was parameterized on the basis of the short-term survival of translocated individuals. There is some evidence that translocated animals have lower survival rates (15–35%) than established animals, especially within 3 mo of the translocation (Jones and Witham 1990; Moehrenschlager and MacDonald 2003; Pinter-Wollman et al. 2009). The reported 7% raptor predation rate (Pertuisel 2010) suggests that the translocated bilbies were experiencing higher than "normal" mortality rates. Raptor predation on nocturnal bilbies should be limited because wedgetail eagles *(Aquila audax)* and hawks are diurnal. Some loss to raptors may occur during twilight hours, and bilby remains have been detected in owl pellets (Department of Biodiversity Conservation and Attractions 2019). However, only one established bilby (samples from 2011 and 2013) was recorded in wedgetail eagle prey remains at Matuwa (Cherriman 2013). We suggest that the majority of the raptor predation events recorded in 2007–2008 are either evidence of unacclimatized bilbies moving during daylight or scavenging. Abnormal data should not be used to define parameters for PVA unless paired with sensitivity testing of the uncertain parameter (Ellner and Fieberg 2003; Bakker et al. 2009; Naujokaitis-Lewis et al. 2009). Sensitivity testing by Pertuisel (2010) did suggest that reducing bilby mortality rate from the 56% measured in the field to 16% would result in a positive growth rate for the population.

Relatively little attention is paid to other environmental variables that may influence the success or failure of translocations of CWR species (Stadtmann and Seddon 2018). As an ex–pastoral lease, Matuwa has vegetation and soil patterns that have been clearly modified by clearing, grazing, and fire. Predator foraging success decreases with habitat complexity, and studies with various prey species have shown selection by prey for more complex habitats as a refuge from predation (Gotceitas and Colgan 1989; Kazantzidis and Goutner 1996). Since the acquisition of Matuwa for conservation in 2000, there has been a consistent increase in the density of vegetation at Matuwa (M. Cowan personal communication). Our findings of higher probability of bilby occupancy in areas with less bare ground and more complex vegetation associations is consistent with other research on foraging success. Cats are likely less successful at capturing bilbies foraging in more complex habitats.

Bilby prevalence at the landscape scale is affected by the availability of key plant foods (Southgate and Carthew 2006) with seed from postfire ephemeral plants an important component of their diet (Southgate and Carthew 2008). Prescribed or wild fires may alter vegetation associations. If fire results in less complex vegetation associations and more bare ground, then foraging success rates for predators are likely to increase. In contrast, fire may increase localized food availablility for bilbies (Southgate and Carthew 2008). Management should aim to reduce the incidence of large bushfires and maximize fire age heterogeneity.

While dense vegetation may inhibit detection of bilbies (Southgate et al. 2005), very dense vegetation is rare on Matuwa. The datum that suggests bilby occupancy is very low when the percentage of bare ground was 1% (see Fig. 5) was collected at a site with 40% cover old mulga (3–6 m high) and dense understory (> 70%) of tussock grasses (*Aristida* sp., *Eriachne* sp., and *Eragrostis* sp.) < 0.5 m high. Conversely, the datum that suggests bilby occupancy is very high when the percentage of bare ground was 10% was collected at a site with very sparse young mulga (1–3 m high), over sparse hummock grasses. Those points may be outliers. Regardless, there is evidence of an interaction between the percentage of bare ground, vegetation associations, and bilby occupancy that should be a priority for further research. Previously, vegetation variables failed to explain much variation in bilby presence (Southgate et al. 2007).

Implications

We have learned several lessons from the only long-term successful reintroduction of bilbies to an open landscape. First, ground- and vehicle-based very-high-frequency tracking is insufficient for monitoring bilbies that are not restricted by fences. Rather, newly translocated bilbies should be monitored via technology that does not depend on our ability to traverse the landscape (e.g., GPS tracking). Established and possibly dispersing bilby populations should be monitored through the expansion of the 2-ha track plot network into neighboring areas (Southgate et al. 2019). Second, translocations should avoid releasing bilbies in groups to minimize the likelihood of surplus killing by predators (Short et al. 2002). Third, methods of reducing predator abundance on a landscape scale (Lohr and Algar 2020) should be implemented for multiple years before reintroducing bilbies to the landscape. Natural bilby populations exist on functioning rangeland pastoral leases that have adopted practices that minimize disturbance to areas of bilby activity (Lavery and Kirkpatrick 1997). The addition of landscape-scale feral cat control to these areas could benefit both the pastoralist by reducing economic loss to cat-borne diseases (Stelzer et al. 2019) and threatened native species. Ultimately, it is inefficient and unethical to reintroduce threatened species to an area when known threatening processes that may have contributed to the extirpation of the species have not first been mitigated (IUCN/SSC 2013).

Future research should address two key questions: 1) What influence does source naivety, site condition, and/or food availability have on the survival rate of translocated bilbies? Our data suggest there may be some interaction between source population and susceptibility to starvation or cat predation, but we do not have the statistical power to confirm those interactions; and 2) Do other species influence bilby persistence—specifically, what multispecies interactions exist among bilbies, introduced predators, introduced herbivores, and vegetation associations? Prior research has found a negative correlation between bilbies and foxes, a positive correlation between bilbies and dingoes (Southgate et al. 2007), and no correlation with vegetation, whereas we have found a positive correlation between bilbies and habitat complexity. It remains difficult to draw management recommendations from the existing research on species associations with bilbies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rama.2021.05.005.

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