



# Predicting suitable release sites for assisted colonisations: a case study of eastern barred bandicoots

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**ABSTRACT:** Assisted colonisations are increasingly being used to recover endangered or functionally extinct species. High quality habitat at release sites is known to improve the success of assisted colonisations, but defining high quality habitat can be challenging when species no longer inhabit their historical range. A partial solution to this problem is to quantify habitat use at release sites, and use results to inform assisted colonisation in the future. In this study, we quantified habitat use by the eastern barred bandicoot *Perameles gunnii*, functionally extinct on the Australian mainland, immediately after translocation to an island ecosystem. The release site, Churchill Island in Westernport, Victoria, Australia, has a mix of open woodlands and open pasture, providing a range of habitat conditions considered appropriate for nesting and foraging. A total of 16 bandicoots were radio-tracked for 30 d immediately post-release. Early survivorship was high (94%), with males found to have larger home ranges and move greater distances from their first nest than females. Males and females initially used structurally complex habitats for nesting and foraging; as they became more established, males moved further from their release point and both sexes increased their use of open habitats during nightly activity. Female home ranges had limited overlap, suggesting intra-sexual territoriality. Males exhibited larger overlapping home ranges. Our results assist in quantifying habitat use of bandicoots immediately post-release and will be used to inform future assisted colonisations of the species to larger islands, in the presence of feral cats.

**KEY WORDS:** Assisted colonization · Island conservation · Endangered species

## INTRODUCTION

Assisted colonisations are the intentional movement and release of organisms outside their indigenous range to avoid extinction of populations of the focal species (IUCN 2013). They have become a critical tool in the conservation of many endemic fauna around the world as invasive species and anthropogenic influences continue to affect their survivorship. The motivations for assisted colonisation are varied; however, their success or failure is determined through 3 key criteria: (1) the initial survival of

the release group, (2) successful breeding by the release group and their offspring and (3) persistence of the established population (Seddon 1999). In each case, the outcome is influenced by several factors including presence of feral predators, release habitats (Sheean et al. 2012) and captive naivety (Mathews et al. 2005). Habitat suitability is even more pertinent when considering the assisted colonisation of a species to a region outside of its indigenous range.

Assisted colonisations are increasingly being used for endangered species where key threatening processes cannot be mitigated within their indigenous

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range. Islands provide ideal locations for assisted colonisations with an increased ability to successfully eradicate invasive species in these ecosystems (Phillips 2010). In Australasia, predator-free islands have enabled the establishment of several species, including the golden bandicoot *Isoodon auratus* (Ottewell et al. 2014), Tasmanian devil *Sarcophilus harrisii* (Thalmann et al. 2016), western barred bandicoots *Perameles bougainville* (Short et al. 1998) and the kakapo *Strigops habroptilus* (Lloyd & Powlesland 1994). Although success has been achieved (Fischer & Lindenmayer 2000), failures highlight the need to understand the factors that enable or prevent these populations from successfully establishing within new environments (Kemp et al. 2015).

Selection of release sites is a critical component of any reintroduction but can be difficult to identify for threatened species with reduced ranges. Habitat suitability for threatened species is often gauged by habitat use within restricted or relic populations that may inhabit sub-optimal regions at the peripheries of their indigenous range (Osborne & Seddon 2012). Given the importance of release site suitability, understanding habitat use immediately post-release when founders are adjusting to new environmental conditions may improve the success rate of future assisted colonisations.

The eastern barred bandicoot *Perameles gunnii* (mainland form, un-named sub-species) was once widespread throughout the tussock grasslands of western Victoria from the South Australian border to Melbourne's western suburbs (Seebeck 1979). Since European settlement, the species has undergone a significant reduction in its range, largely attributable to habitat loss and predation by the introduced red fox *Vulpes vulpes* (Seebeck 1979). Such population pressures have resulted in the species being listed as endangered under the Commonwealth Environmental Protection and Biodiversity Conservation Act 1999 and as extinct in the wild by the Victorian Department of Environment, Land, Water and Planning's (DELWP) Advisory List of Threatened Vertebrate Fauna (Department of Sustainability and Environment 2013). In an attempt to re-establish viable populations, reintroductions at 9 locations within the indigenous range have been attempted with varying levels of success (Winnard & Coulson 2008). Predation by red foxes *V. vulpes* is the primary reason for reintroduction failure, a problem exacerbated by poor quality habitat and drought (Todd et al. 2002, Winnard & Coulson 2008). Studies of habitat use within the indigenous range have shown that bandicoots require a mix of structurally complex habitats

for nesting and open habitats for foraging (Dufty 1994, Cook et al. 2010, Winnard et al. 2013).

In 2015, eastern barred bandicoots persisted across 5 geographically isolated populations (Parrott et al. 2017) ranging in size from ~60 individuals in the captive insurance population to around 1000 individuals at Mt. Rothwell (D. Sutherland unpubl. data), with all bandicoots, from all sites, being descendants of 19 founder individuals (Weeks et al. 2013). In 2010, genetic diversity in the remaining mainland bandicoot population had dropped by 35 to 40% from the level in 1990. To prevent further loss of diversity, a rapid population increase to 2500 individuals is required (Hill et al. 2010). To achieve this, the Eastern Barred Bandicoot Recovery Team has initiated projects to establish the species on fox-free islands, where threats can be managed effectively (Coetsee 2016, Hill et al. 2018).

In this study, we aimed to assess the survival and habitat use of bandicoots immediately post-release in a novel environment to help inform future assisted colonisations of the species. Specifically, we aimed to quantify habitat use through assessment of the importance of structurally complex habitats, how habitat use changed over the first 30 d post-release and whether there were sex- or origin-based differences.

## MATERIALS AND METHODS

### Study species and location

Eastern barred bandicoots (hereafter 'bandicoots') are small marsupials, with adults weighing from 600 to 1000 g. Bandicoots typically live 2 to 3 yr and can produce up to 5 litters of 1 to 4 young yr<sup>-1</sup>, if conditions allow (Dufty 1995). They are strictly nocturnal, nesting during the day in leaf litter or grass-lined nests hidden in a small scrape usually within structurally complex habitats, then emerging at night to forage in open habitats (Dufty 1991, Winnard et al. 2013). Their diet consists largely of invertebrates on or under the soil surface such as earthworms, various beetle larvae (coleopteran and lepidopteran) and adults (Coleoptera), as well as vegetative material including grass and roots (Reimer & Hindell 1996).

Churchill Island (38° 29' 59" S, 145° 20' 19" E) is 52 ha in size, 91 km south-east of Melbourne beyond the indigenous range of the species (Fig. 1). Churchill Island sits off the northern coastline of Phillip Island and is connected by a 100 m concrete bridge. Biosecurity measures are in place to prevent incursions of introduced red foxes, feral cats and rabbits *Oryctola-*



Fig. 1. Outline of Victoria, Australia, with historical eastern barred bandicoot distribution shown in grey. Zoomed-in aerial view illustrates the broad habitat types of Churchill Island within Victoria

*gus cuniculus*, including intense fox control (Kirkwood et al. 2014, Rout et al. 2014) and a predator-resistant gate that is shut from dusk to dawn. Two-thirds of the island is operated as a heritage farm with grazing sheep, cattle and horses, while the remainder of the island supports regenerating bushland consisting of swamp paperbark *Melaleuca ericifolia*, eucalyptus *Eucalyptus globulus* and moonah *Melaleuca lanceolata* ssp. *lanceolata* shrublands. The understorey is dominated by introduced pasture grasses with coastal tussock-grasses *Poa labillardierei* var. *labillardierei*, blue tussock grass *Poa poiiformis* and seaberry saltbush *Ragodia candolleana* ssp. *candolleana* scattered throughout. In this study, habitat was characterised into 4 broad types: tea tree woodlands (thick swamp paperbark with an open understorey); coastal mixed woodlands (sparse moonah woodlands, with a mixed understorey of tussock grass and seaberry saltbush); mixed woodlands (mature eucalyptus and immature moonah woodlands, with a variable understorey of tussock grass and unmanicured pasture grass); and pasture (pasture grass).

Churchill Island was chosen as the release site for bandicoots due to the absence of introduced pest species and the presence of woodland and open pasture considered suitable for bandicoots, as it provides

habitat for both nesting and foraging (Dufty 1994, Winnard & Coulson 2008). Native predators including the eastern barn owl *Tyto javanica* and the southern boobook *Ninox boobook* are both known to occur on the island and surrounding landscape.

### The release

A total of 16 bandicoots were translocated to Churchill Island on 16 August 2015. Eight came from Zoos Victoria's captive-breeding program, and a further 8 were translocated from the free-ranging population at Mt. Rothwell Biodiversity Interpretation Centre near Lara (37° 53' 41.68" S, 144° 26' 18.35" E), a grassy woodland reserve with basaltic stony rises surrounded by a predator barrier fence (see Winnard et al. 2013). An equal sex ratio was taken from each source population. Free-ranging bandicoots were captured the evening prior to release and all animals were transported to the release site on the day of release.

Bandicoots were hand released (de Milliano et al. 2016) after dusk at the interface between either tea tree woodlands or mixed woodlands (i.e. structurally complex habitats) and pasture.

### Health assessments

Bandicoots were live-trapped 2 and 4 weeks post-release to assess health and body condition. Wire cage traps (length × width × height: 50 × 18 × 20 cm) baited with a mix of rolled oats, peanut butter and golden syrup were placed around bandicoot nesting locations and in nearby foraging areas, and deployed for 4 consecutive nights. Captured bandicoots were weighed and their physical condition assessed. Females' pouches were checked for pouch young and their respective developmental stage recorded.

### Radio tracking

Each bandicoot was fitted with a 2.5 g transmitter with a 120 mm whip antenna mounted on cable-tie collars (Coetsee et al. 2016). Individuals were tracked

using a yagi antenna (Sirtrack) and receiver (R1000, Communication Specialists). Locations of animals active at night were determined each night for up to 30 d. Where possible, each bandicoot was observed each evening to verify that movements were unimpeded by the collar (as this was the first test of the collar on free-ranging bandicoots); when bandicoots were in dense vegetation, locations were estimated by in-field triangulation. All triangulations were across short distances, meaning we could confidently assign locations to habitats used. Each bandicoot was located once per night to ensure independence of fix locations. The order of individuals in which fixes were taken differed nightly to reduce any temporal bias. Nest site locations were determined each day for 1 wk post-release and approximately twice-weekly thereafter. Plant species under which bandicoots nested were recorded for each location. All locations were taken using a Hemisphere R110 differential GPS ( $\pm 0.5$  m), and the activity (nesting, foraging) of the individual was recorded. All collars were removed 30 d post-release in response to welfare concerns for collared bandicoots as a result of a bandicoot being detected with a foreleg entangled in the collar.

### Statistical analysis

#### Home range size

Home range size and utilisation distributions for each individual were calculated using kernel estimators. Initially, smoothing parameters were not able to be minimised through least squares cross validation due to the presence of multiple identical relocations (i.e. repeated use of the same nest site). This is a known problem with kernel estimators; therefore, we removed repeated diurnal nesting locations ( $n = 68$ , mean = 4.25, median = 4) from the data (Calenge 2011). A fixed kernel with least squares cross validation was used to determine the smoothing parameter for each individual. Over-smoothing was observed for some individuals (Kernohan et al. 2001); to ensure consistency, the same smoothing parameter was used for each individual. The largest smoothing parameter generated through least squares cross validation was applied to all individuals. This ensured that consistent smoothing parameters were applied throughout, while preventing over-smoothing of these data. Incremental area analysis was conducted to determine whether our estimates were likely to be reflective of the individuals' overall range. Minimum con-

vex polygons (95%) were also calculated to enable comparison with prior studies on the same species (Ferguson 2006, Winnard et al. 2013, Groenewegen et al. 2017).

The level of spatial overlap between individuals (male–male; female–female; male–female) was determined with the use of Bhattacharyya's affinity (BA). BA reflects the level of overlap between 2 individuals' home ranges on a scale from 0 to 1, where BA = 0 indicates no overlap and BA = 1 indicates complete overlap. This statistic has been shown to perform best for home range overlap analysis if the aim is to quantify the overall similarity between 2 utilisation distributions (Fieberg & Kochanny 2005).

#### Habitat selection

Nocturnal habitat selection was determined for all individuals for which a utilisation distribution could be calculated ( $n = 15$ ). An Eigen-analysis of selection ratios for design II studies was conducted to explore habitat selection by bandicoots (Calenge & Dufour 2006). The Eigen-analysis is a non-centred and non-scaled principal component analysis that compares the availability of each habitat to the habitats used by particular individuals (i.e. selection ratios). Design II studies distinguish between individuals, but assume that habitat availability is the same for all animals. Churchill Island was classified into 4 broad habitat types: tea tree woodlands; coastal mixed woodlands; mixed woodlands; and pasture. These classifications were selected to reflect habitats that have been identified as important in previous studies (Dufty 1994, Mallick et al. 1997), with the addition of coastal environments.

#### Change in habitat use through time

Habitat structural complexity was determined for each bandicoot location from LiDAR point cloud data collected in 2008. A digital elevation model (DEM) and a digital surface model (DSM) were generated representing the ground/topography and the highest point above ground (i.e. tree canopy, building roof) respectively. The DSM was subtracted from the DEM to produce a layer of habitat structure at a 1 m<sup>2</sup> resolution. Visual inspection of these data revealed that a section of tea tree had become established since the 2008 LiDAR data was produced. Therefore, pixel values of regions now with tea trees were isolated from recent (2015) air photos (10 cm resolution) and values

increased to more accurately reflect the vegetative structure of Churchill Island at the time of the study. Bandicoot locations were buffered to 10 m, with the average height of vegetation within each buffer zone used to reflect the structural complexity of each bandicoot relocation. This measure of structural complexity has limitations in that tall overstorey with sparse understorey will be considered complex habitat; however, this is a more generalisable metric of habitat, with ground truthing supporting it as a reasonable measure of complexity.

Generalised linear mixed models (GLMMs) were used to identify potential habitat and temporal parameters driving habitat use by bandicoots. Where residual plots suggested non-linear relationships, generalised additive mixed models (GAMMs) were used. Candidate models were created to test (1) whether bandicoots increased their distance travelled over time and (2) whether the structural complexity of habitat used by bandicoots changed over time. Differences between the sexes and origin (captive or free-ranging) were considered in each model, with interactions between sex and days since release and origin and days since release included to allow for changes in habitat use by one sex or origin to vary independently of the other. Nocturnal (foraging) and diurnal (nesting) fixes were analysed in separate models. Bandicoot identity was included as a random factor in all models to account for the innate dependency between locations for the same individual. Models were run with either an underlying Poisson or Gaussian distribution, based on visual inspection of the data. Where over-dispersion was detected within the data, a negative binomial distribution was used. Colinearity between explanatory covariates was assessed within each model. Only covariates with a Pearson correlation coefficient  $<0.4$  were included within the same model. Residual plots of observed versus fitted values, and fitted values compared to each parameter within the model were used to validate each model. A fixed variance structure was applied to the GLMM of nocturnal distance from first nest to account for heterogeneity patterns in the residuals. Once validated, Akaike's information criterion corrected for small sample sizes ( $AIC_c$ ) was used to determine the most parsimonious model.

All analyses were run in R (R Development Core Team 2017), with home range and utilisation distributions calculated through 'adehabitatHR' and habitat selection analysis conducted within 'adehabitatHS' (Calenge 2006). GLMMs were run in 'mgcv' (Wood 2011) or 'lme4' (Bates et al. 2015) and GAMMs in 'gamm4' (Wood & Scheipl 2014). Model selection

was performed with 'AICcmodavg' (Mazerolle 2016) and R-squared values calculated in 'MuMIn' (Barton 2016). Habitat categories were created and manipulated in QGIS 2.10.1-Pisa (QGIS Development Team 2016) at a scale of 1:500. Habitat structural complexity was calculated from LiDAR data collected using a Leica ALS50 sensor with a vertical accuracy of 0.1 m with DEMs and DSMs created in ArcGIS 10.1 (ESRI 2012).

## RESULTS

### Survival

The survival rate of founding individuals was 94 % after 1 mo. Three females were translocated from Mt. Rothwell carrying two  $\leq 25$  d old unfurred pouch young each; all pouch young survived the translocation process. One death of a captive-raised bandicoot occurred 7 d after the initial release. The individual was considered to have been unable to adapt to the wild; an autopsy revealed severe dehydration and emaciation, with no food observed within the stomach and a 30% reduction in body weight since release. The majority of individuals gained weight throughout the first month, with breeding observed in the field and pouch young conceived on Churchill Island detected within 4 wk of release.

### Radio tracking

A total of 500 location fixes were collected from 16 bandicoots. Of these, 185 were diurnal nesting locations and 315 nocturnal fixes (foraging  $n = 204$ ; moving  $n = 111$ ). A total of 15 bandicoots had a minimum of 24 fixes (mean = 27) that were used for home range analyses (males  $n = 8$ ; females  $n = 7$ ). Males were found to have larger home ranges (95% utilisation distribution [UD], a smoothing parameter: mean = 19.5 ha; range: 16.6 to 23.1;  $h = 40.1$ ) than females (mean = 9.0 ha, range: 5.6 to 15.24;  $h = 40.1$ ) (Table 1). Females showed less spatial overlap ( $BA = 0.17$ ) than did males ( $BA = 0.47$ ), while male and female home ranges showed some overlap ( $BA = 0.36$ ).

### Habitat selection

Bandicoots nested within a wide range of vegetation classes (Fig. 2). Habitats dominated by native tussock grasses were the most commonly used nest-

Table 1. Demographic and home range data for released eastern barred bandicoots on Churchill Island. Bandicoot release weight, minimum convex polygons (MCP) and utilisation distributions (UD) are presented (means  $\pm$  SD). Asymptote signifies whether sufficient data were collected to provide a fully representative UD; presented as proportion of home ranges that reached an asymptote, versus those that did not. Calculations were not made for 1 bandicoot due to a limited number of locations obtained ( $n = 13$ ) of which few were active fixes ( $n = 6$ )

Source population	Sex	Release weight (g)	95 % MCP (ha)	95 % UD (ha)	Asymptote
Captive	Female	612.5 $\pm$ 40.3	4.09 $\pm$ 3.37	10.37 $\pm$ 4.32	0/3
Captive	Male	741.8 $\pm$ 100.6	8.57 $\pm$ 0.98	18.58 $\pm$ 1.34	2/4
Free-ranging	Female <sup>a</sup>	595.3 $\pm$ 81.1	1.33 $\pm$ 1.24	11.95 $\pm$ 2.44	2/4
Free-ranging	Male	584.0 $\pm$ 59.2	17.26 $\pm$ 11.27	20.43 $\pm$ 2.81	1/4

<sup>a</sup>Three females were carrying 2 pouch young each

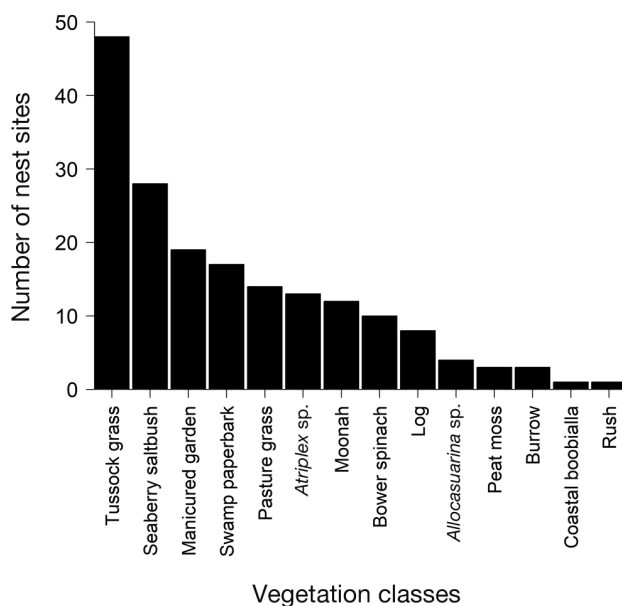


Fig. 2. Nest site selection of eastern barred bandicoots across 30 d immediately post-release on Churchill Island, Victoria

ing sites (either blue tussock grass or coastal tussock grass) followed by seaberry saltbush *Rhagodia candolleana*. Nests were found in more structurally complex habitats with leaf litter used for nest construction at the base of trees (moonah, swamp paperbark, *Allocasuarina* sp.) or under dense ground-storey vegetation (tussock grass, seaberry saltbush and *Atriplex* sp.). Bandicoots also opportunistically used logs, burrows and ornamental shrubs in managed gardens as nest sites.

Bandicoots foraging at night were found to use particular habitats more than were available. However, the habitats that were used differed between individuals. Female bandicoots utilised coastal woodlands more than expected, while individuals sourced from

free-ranging populations used a wider variety of available habitats (Fig. 3). Several bandicoots used the coastal boundary of the island more than was expected, with 2 female free-ranging bandicoots heavily selecting for this habitat (Fig. 3). Only one individual, a female free-ranging bandicoot, used pasture more than was available. Some bandicoots selected a mosaic of habitat types and were found to use them similarly to their availability, particularly a captive female who frequently used high structure mixed woodlands and coastal woodlands (Fig. 3).

#### Change in habitat use through time: distance to first nest

The global model of nocturnal fixes including time since release, sex, origin and both 2-way interaction terms was found to be strongly supported by the data (Table 2). Bandicoots increased the distance travelled between their first nest and foraging sites over time, with shorter distances travelled immediately post-release and larger movements travelled as time since release increased. Males travelled considerably further than females (Fig. 4). Whether individuals were from a captive population or free-ranging population also influenced their distance moved, with free-ranging individuals travelling further than captive individuals (Fig. 5).

The best supported model of diurnal fixes included time since release with a smoothing parameter and origin of individual (Table 2). Over time, bandicoots moved further away from their first nest, with captive individuals moving greater distances between nest sites than free-ranging individuals (Fig. 6). Neither sex nor the interaction between sex and time since release were present in the top models, suggesting there was limited support for a difference between sexes in the distance moved from first nest.

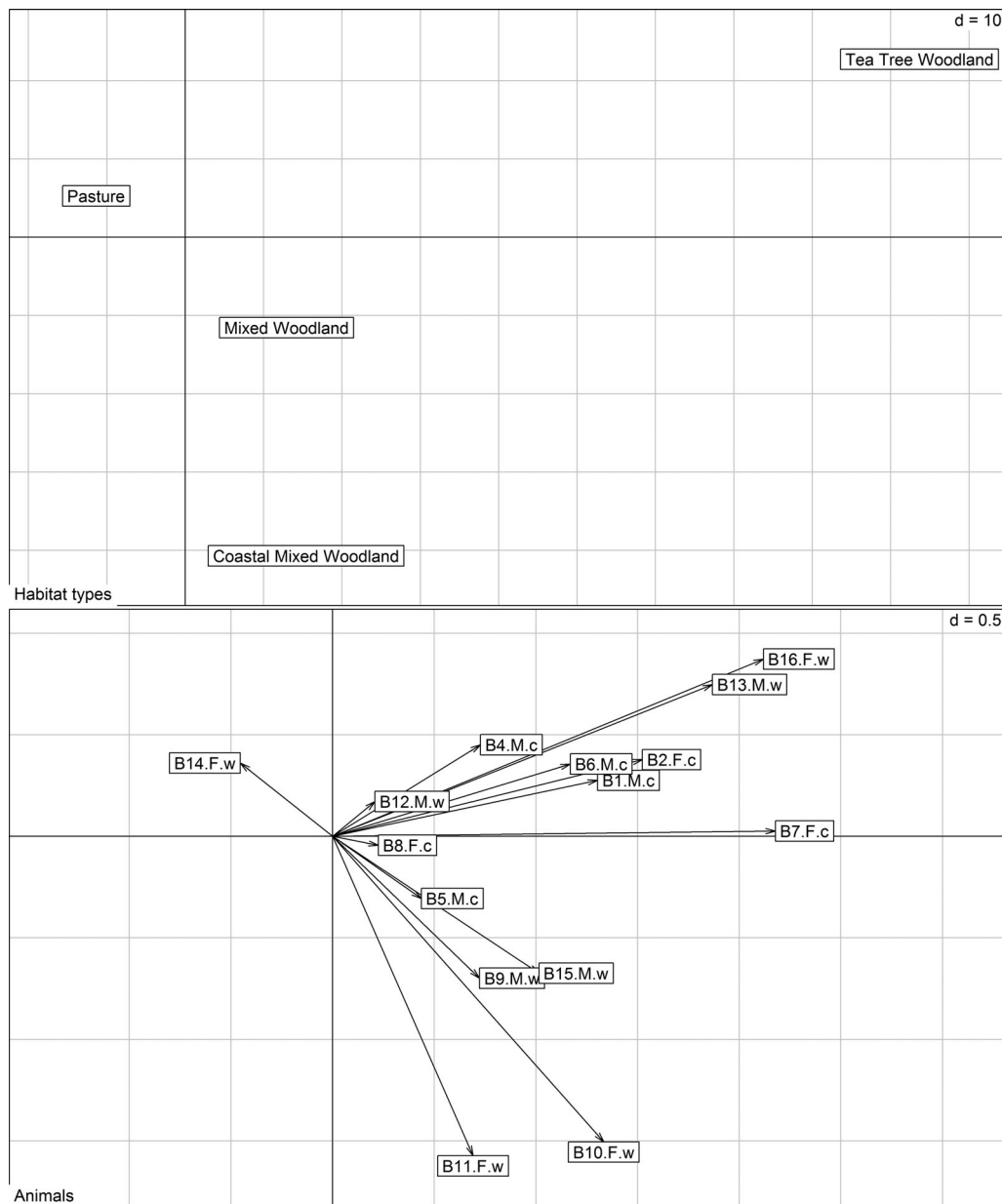


Fig. 3. Eigen-analysis of selection ratios representing the primary habitats selected by eastern barred bandicoots during nocturnal foraging. Top panel represents available habitats; bottom panel demonstrates how closely related individual bandicoots were to particular habitats. The more a bandicoot location overlaps with a habitat type, the more exclusively this habitat was used by that individual. Where bandicoot locations fall between 2 habitats, the individual used both habitat types. Labels represent whether the bandicoot was male (M) or female (F), and whether they were from captive (c) or free-ranging (w) populations

#### Change in habitat use through time: habitat structural complexity

There was considerable model selection uncertainty, with the top 3 models receiving  $AIC_c$  scores  $<2$  and with all models explaining  $<8\%$  of variation within these data (Table 2). The poor explanatory

power of these models suggests that structural complexity of habitat may have a limited relationship with bandicoot activity. Our results do suggest that, while bandicoots were active, low structurally complex habitats were used more frequently as time since released increased; and free-ranging bandicoots used open habitats more than captive individuals.

Table 2. Models considered to describe nocturnal and diurnal habitat use by eastern barred bandicoots in relation to their use of habitat structural complexity and the change in distances moved from nest locations to foraging sites. Models are ranked based on Akaike’s information criteria corrected for small sample sizes ( $AIC_c$ ). Reported are the number of parameters within the model (K), the difference from the model with lowest  $AIC_c$  ( $\Delta AIC_c$ ), model  $AIC_c$  weights ( $AIC_c \omega$ ) and adjusted R-squared values ( $R^2$ ). Model parameters include distance to first nest (Dist), structural complexity of habitat (Struc), time since release (TSR), whether an individual was from a captive or free-ranging population (Origin), and constant model (1); s(x) indicates where a smoothing parameter has been applied. GLMM: generalised linear mixed model; GAMM: generalised additive mixed model

Model	Type	Model formula	K	$AIC_c$	$\Delta AIC_c$	$AIC_c \omega$	$R^2$
Distance to first nest: nocturnal	GLMM	Dist = TSR + Sex + Origin + TSR × Sex + TSR × Origin	8	3899.71	0.00	1	0.409
		Dist = TSR + Sex + Origin + TSR × Sex	7	3913.44	13.73	0	0.298
Distance to first nest: diurnal	GAMM	Dist = s(TSR) + Origin	6	1772.85	0.00	0.76	0.172
		Dist = s(TSR, by Origin) + Origin	8	1776.68	3.83	0.11	0.198
		Dist = s(TSR)	5	1777.14	4.29	0.09	0.093
		Dist = s(TSR) + Sex	6	1778.83	5.98	0.04	0.107
		Dist = s(TSR, by Sex) + Sex	8	1782.23	9.38	0.01	0.127
Use of structure: nocturnal	GLMM	Struc = TSR + Origin + TSR × Origin	6	1230.53	0.00	0.41	0.071
		Struc = TSR + Origin	5	1231.13	0.59	0.30	0.062
		Struc = TSR + Sex + Origin + TSR × Origin	7	1231.92	1.39	0.20	0.073
		Struc = TSR + Sex + Origin + TSR × Origin + TSR × Sex	8	1233.61	3.08	0.09	0.074
Use of structure: diurnal	GLMM	Struc = TSR + Sex + Origin + TSR × Sex	6	673.40	0.00	0.51	0.212
		Struc = TSR + Sex + TSR × Sex	5	674.31	0.91	0.32	0.130
		Struc = TSR + Sex + Origin + TSR × Origin + TSR × Sex	7	675.56	2.16	0.17	0.211

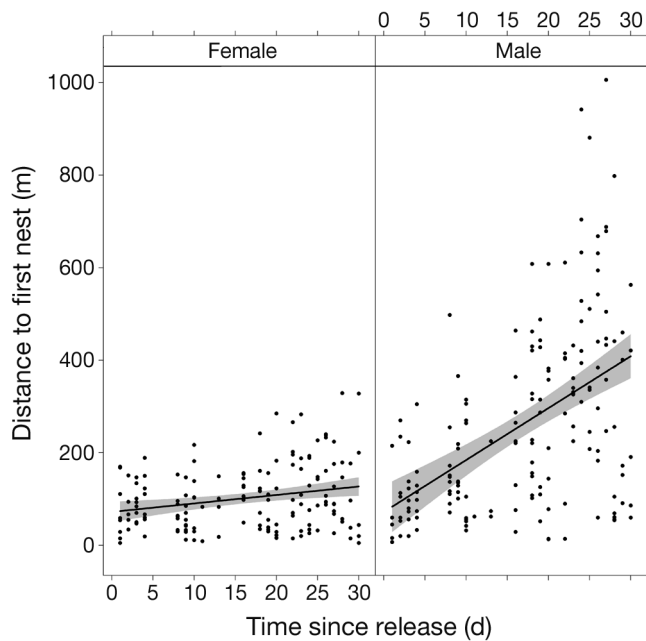


Fig. 4. Relationship between time since release of eastern barred bandicoots and the nocturnal distances moved from their first nest after translocation for each sex

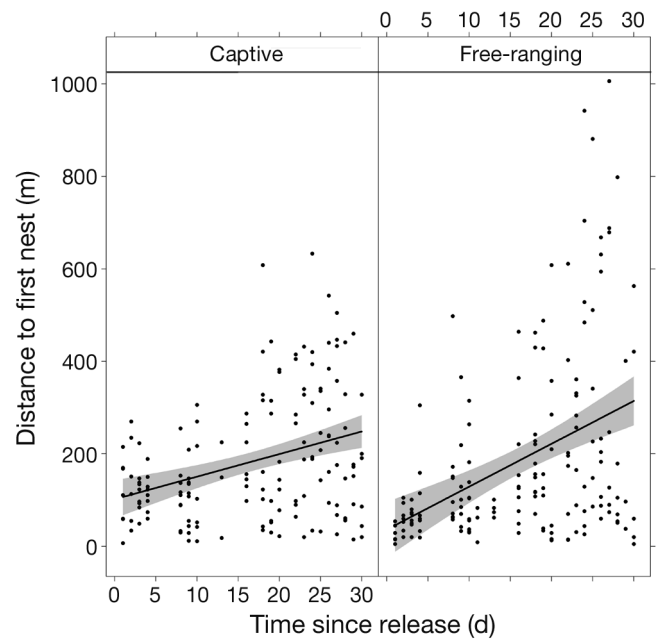


Fig. 5. Relationship between time since release of eastern barred bandicoots and the nocturnal distances moved from their first nest after translocation dependent on whether the individual was from a captive or free-ranging population

The structural complexity of habitats used while nesting was associated with time since release, sex, origin and an interaction term between time since release and sex. However, there was model selection uncertainty (Table 2). Females initially used more structurally complex habitats using lower structure

for nesting through time, whereas males initially used lower structural complexity using more complex nesting sites through time (Fig. 7). Despite these shifts, bandicoots were not found to use nest sites with less than 1 m of structural complexity on average. Origin of individuals had a weak relationship



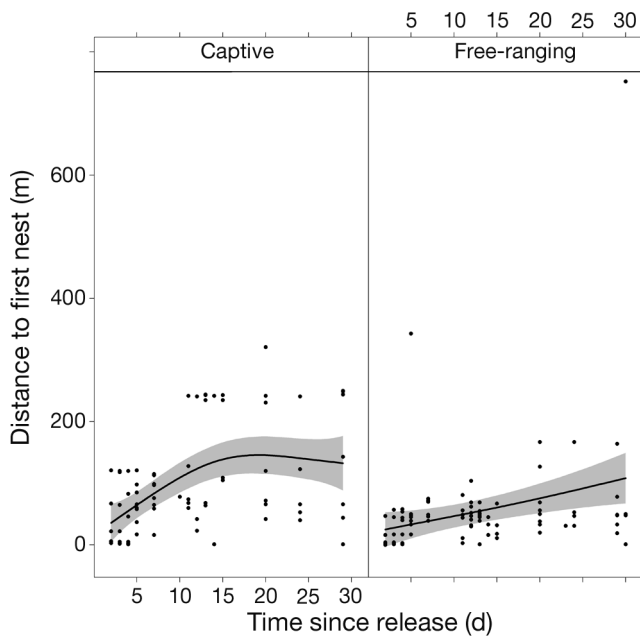


Fig. 6. Relationship between time since release of eastern barred bandicoots and the diurnal distances moved from their first nest after translocation dependent on whether the individual was from a captive or free-ranging population

with vegetation complexity, with free-ranging individuals suggested to use less structurally complex habitats as time since release increased. This trend had limited power to explain the variation within the data (Table 2).

## DISCUSSION

Assisted colonisations are a valuable conservation tool; however, limited research has focused on the factors that enable or prevent their success. Here, we demonstrated how monitoring habitat use post-release can provide important information required to inform and potentially improve the success of future assisted colonisations. Bandicoots were found to initially use more structurally complex habitats for both nesting and foraging than available, a result potentially influenced by their release locations. However, as they became more established within their new environment they expanded their movements from their point of release. Males in particular moved further between their nesting and foraging sites and started using less structurally complex habitats. This trend supports the findings of studies in more established populations, where individuals showed a willingness to forage exclusively in less structurally complex habitats (Winnard et al. 2013).

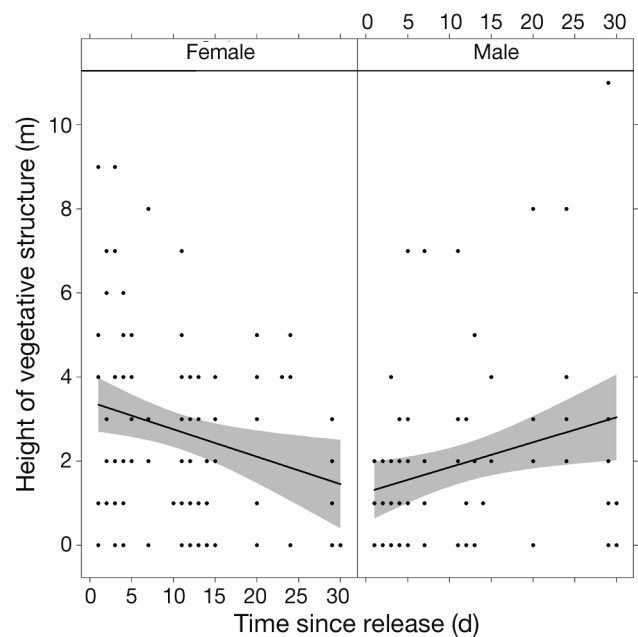


Fig. 7. Height of habitat structural complexity within a 10 m radius of eastern barred bandicoot nesting locations in relation to time since release and bandicoot sex

The initial use of structurally complex habitats and limited range expansion has been observed before (Winnard 2010) and may provide individuals with greater protection from potential predators. This is an important consideration for future assisted colonisations to islands where invasive predators such as feral cats are not able to be eradicated. Studies in the presence of invasive predators suggested an absence of structurally complex habitat may have limited bandicoot distributions (Brown & Seebeck 1989). Research has also highlighted how invasive predators can be less successful when foraging within more complex habitats (McGregor et al. 2015); as such, releasing individuals into structurally complex habitats may provide greater survival in the presence of predators.

The origin of individual bandicoots was found to influence how they used habitat on release. Free-ranging individuals sourced from Mt. Rothwell, a 420 ha predator-proof fenced enclosure, moved greater distances and used less structurally complex habitats than those sourced from Zoos Victoria's captive breeding program. This may reflect less habitat awareness of captive-bred individuals compared to free-ranging bandicoots. Studies of captive-bred versus wild individuals have found evidence of maladaptation in captive individuals, as they spend more time on unnecessary tasks and are less adapted to

accessing wild food sources (Mathews et al. 2005). Captive-bred bandicoots, however, have regularly and successfully been used for reintroductions into their former range, and there appears to be no difference in their survival within the present study. The absence of cursorial predators on Churchill Island may have enabled higher survivorship irrespective of origin. Studies of burrowing bettongs *Bettongia lesueur* have demonstrated that wild translocated individuals were capable of altering their behaviour in the presence of a low density feral cat population (West et al. 2018). Future releases may need to consider the habitat awareness of captive and free-ranging individuals and how this might influence survival in the presence of invasive predators.

Habitat structural complexity was found to have an influence on bandicoot nest site selection; however, both males and females nested below vegetation of at least 1 m in height on average. Although shifts in male and female use of structural complexity for nesting were identified, this is likely a reflection of limited sample size and insufficient resolution within these data. Given the 10 m radius analysed here, nest site selection may be influenced on a smaller spatial scale. Bandicoot nocturnal habitat use throughout the study supports their initial use of structurally complex habitats and demonstrates their generalist nature, with all available habitat types used by different individuals. Similar results were found from suitability models where, despite a considerable range of vegetation types and species being modelled, none were found to be explanatory of bandicoot persistence at a site (Cook et al. 2010). The species has also been found to persist within degraded landscapes with limited vegetation due to over-grazing by macropods (Winnard et al. 2013). As a result, bandicoots are ideal candidates for assisted colonisations and are likely capable of occupying all available habitats on larger proposed islands (Coetsee 2016, Hill et al. 2018).

The home range sizes of released individuals are consistent with those of studies in more established populations. In the present study, male bandicoots had a mean home range of 19.5 ha; more than double that of females at 9.0 ha. Previous studies of established populations within a degraded landscape similarly found male ranges (37.2 ha) to be double the size of female ranges (15.8 ha) (Winnard et al. 2013). The size of Churchill Island limits the space available to individuals, though not all of the island was used by males or females, suggesting range expansion was possible. This study is the first to be able to track all individuals simultaneously,

something previously not possible due to issues with collar attachment (Coetsee et al. 2016). This revealed that females showed a lower level of home range overlap than males, suggesting territoriality between females. Intra-sexual territoriality has been observed in other marsupials including the spotted-tailed quoll *Dasyurus maculatus* (Belcher & Darrant 2004), chuditch *Dasyurus geoffroii* (Serena & Soderquist 1989), northern quoll *Dasyurus hallucatus* (Oakwood 2002) and brush-tailed phascogale *Phascogale tapoatafa* (Soderquist 1995). Female territoriality has been associated with protection of food resources in microtine rodents (Ostfeld 1985). Such resource protection may provide areas for offspring to forage with reduced competition prior to dispersal from their natal home range. An alternative hypothesis is the offspring-defence hypothesis, which suggests that it may act as a preventative of infanticide from rival females (Wolff & Peterson 1998). Infanticide was not observed, and has not been found for bandicoot species. It is considered rare in marsupials as most carry altricial young within their pouch. Intra-sexual territoriality within endangered species has implications for the management of their meta-populations. For eastern barred bandicoots there are currently 3 additional sites supporting bandicoots across Victoria (Hamilton Community Parklands, Mt. Rothwell and Woodlands Historic Park), with new sites under development (Coetsee 2016, Hill et al. 2018). However, as independent sites they are too small to halt a continued loss of genetic diversity (Weeks et al. 2013), hence these populations are managed as a single meta-population with adults introduced from the captive population into each site to increase genetic diversity (Hill et al. 2018). Given intra-sexual territoriality, females introduced into established populations may be outcompeted for space by conspecifics, limiting their chance to contribute to the genetics of the population. Males, on the other hand, may be more likely to successfully breed, yet may still experience intraspecific competition from rival males. One possible solution could be to introduce individuals as others are removed to contribute to new populations or the breeding program. In these circumstances, 'space' within the established population will become available for these new individuals to occupy. Determining the survival and breeding success of individuals introduced into established populations is a research priority.

Assisted colonisations into novel habitats are increasingly being used as a tool for conserving many endangered species (Seddon et al. 2015) when op-

tions for release within their indigenous ranges are limited. Here, both male and female bandicoots remained close to their release sites for the first 2 wk post-release. Future releases onto larger islands where invasive predators such as feral cats are present should consider release sites within more structurally complex habitats, less favourable to these predators, to improve survivorship of founding individuals. The ability to monitor 16 individuals simultaneously marks an improvement in our ability to monitor this species; however, problems with collar attachment did result in a reduced sample size, limiting our inferential power. Regardless, this study highlights the value of post-release monitoring in assisted colonisation campaigns and demonstrates how insights from monitoring can be used to inform and improve future colonisations.

**Acknowledgements.** This project was undertaken in accordance with the regulations of Phillip Island Nature Parks Animal Ethics committee under Project No. 3.2015 and in accordance with the Department of Environment, Land, Water and Planning (DELWP), Research Permit No. 1000-7613. Funding support was provided by Zoos Victoria. Thanks to Peter Dann for his work in establishing this project, and to Mt. Rothwell Biodiversity and Interpretation Centre, Zoos Victoria, DELWP and the members of the Eastern Barred Bandicoot Recovery Team, without whom this project would not have been possible. Thanks to Julian Di Stefano for comments on an earlier version of the manuscript. Finally, thanks also to the many volunteers who helped and provided assistance in the field.

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