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Review

Verifying bilby presence and the systematic sampling of wild populations using sign-based protocols – with notes on aerial and ground survey techniques and asserting absence

Richard Southgate[A], *Martin A. Dziminski*[B,E], *Rachel Paltridge*[C], *Andrew Schubert*[C] *and Glen Gaikhorst*[D]

[A]Envisage Environmental Services, PO Box 305, Kingscote, SA 5223, Australia.
[B]Department of Biodiversity, Conservation and Attractions, Western Australia, Woodvale Wildlife Research Centre, Locked Bag 104, Bentley Delivery Centre, WA 6983, Australia.
[C]Desert Wildlife Services, PO Box 4002, Alice Springs, NT 0871, Australia.
[D]GHD Pty Ltd, 999 Hay Street, Perth, WA 6004, Australia.
[E]Corresponding author. Email: martin.dziminski@dbca.wa.gov.au

Abstract. The recognition of sign such as tracks, scats, diggings or burrows is widely used to detect rare or elusive species. We describe the type of sign that can be used to confirm the presence of the greater bilby (*Macrotis lagotis*) in comparison with sign that should be used only to flag potential presence. Clear track imprints of the front and hind feet, diggings at the base of plants to extract root-dwelling larvae, and scats commonly found at diggings can be used individually, or in combination, to verify presence, whereas track gait pattern, diggings in the open, and burrows should be used to flag potential bilby activity but not to verify presence. A protocol to assess potential activity and verify bilby presence is provided. We provide advice on the application of a plot-based technique to systematically search for sign and produce data for the estimation of regional occupancy. Digging and burrow activity can be readily detected from the air but systematic ground-based assessment to determine the rate of false-presence and false-absence needs to accompany aerial survey. The approach to estimate survey effort to assert bilby absence is also described.

Additional keywords: CyberTracker, detection, Indigenous rangers, marsupial, occupancy, root-dwelling larvae, tracking.

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Introduction

The greater bilby (*Macrotis lagotis*) is a species with taxonomic, cultural (Paltridge 2016; Walsh and Custodians of the Bilby 2016) and iconic significance (Bradley *et al*. 2015). It is federally and internationally listed as vulnerable (EPBC 1999; Burbidge and Woinarski 2016; Department of Environment 2016) and still declining in distribution (Bradley *et al*. 2015). It is considered beneficial as an ecosystem engineer (James and Eldridge 2007; Read *et al*. 2008; Newell 2008; James *et al*. 2011; Fleming *et al*. 2014; Hofstede and Dziminski 2017) and an indicator species of environmental conditions (Southgate 1994). Refining methods to survey and monitor is acknowledged as a research priority for the conservation of this species (Woinarski *et al*. 2014; Bradley *et al*. 2015; Cramer *et al*. 2016). Unbiased data are required to correctly determine threatened status (IUCN 2012) or assess the response of a population to management (Lyons *et al*. 2008). Additionally, an assessment to assert whether a threatened species of significance is present or not within a proposed development site is mandatory at both the Federal (Commonwealth of Australia 2012) as well as the State and Territory levels of government in Australia.

Because the species is sparsely distributed and difficult to observe and capture (Southgate *et al*. 1995), monitoring of wild bilby populations has relied largely on sign-based data, including tracks (Southgate *et al*. 2005) and burrows and diggings (Lavery and Kirkpatrick 1997; McRae 2004; Burrows *et al*. 2012) to assess relative abundance or frequency of occurrence (Southgate *et al*. 2005; Southgate *et al*. 2007*a*). Of the methods applied, the 2-ha plot-based sampling technique has become the most widely adopted (Bradley *et al*. 2015; Paltridge 2016). It has been applied by many Indigenous Ranger Groups to survey for bilbies (Paltridge 2016) and to monitor a range of other species in the arid and semiarid parts of Australia (Pedler *et al*. 2016). It can be used to systematically record the presence or absence of a suite of medium- to large-sized target species at a location (Moseby *et al*. 2009). This includes native mammal and bird species, introduced predators and introduced herbivores typically larger than 100 g. Species occurrence is based primarily on the detection and interpretation of tracks but can be extended to include other sign (e.g. scats, diggings) to verify presence.

However, in common with other sign-based protocols, problems can arise if observational accuracy is poor because of non-detection and misidentification error (Pollock *et al*. 2002; Miller *et al*. 2011; Rhodes *et al*. 2011). In determining the fraction of sites in a landscape where a focal species is present there are four possible states when a site is sampled (Wintle *et al*. 2012): the site is occupied and a species is detected (true presence), the site is unoccupied and the species is not detected (true absence), the site is occupied but the species is not detected (false absence) and the site is unoccupied but the species is misclassified as present (false presence).

Provided that repeat sampling of sites can be conducted within a relatively short time frame, several analytical methods have been devised to address false-absence detection error and produce less biased estimates of occupancy (MacKenzie *et al*. 2002; Tyre *et al*. 2003). These models generally assume that there are no misclassified observations (Royle and Link 2006) and samples are spatially and temporally independent (MacKenzie *et al*. 2002). Misclassified observation can occur if the sign left by a species is wrongly identified (e.g. bilby activity is ascribed to goanna diggings) or wrongly aged (e.g. old bilby activity ascribed to fresh sign). Both examples would incorrectly inflate actual bilby occupancy estimates.

Occupancy models also presuppose that samples are collected randomly and not skewed to sites known to be occupied (MacKenzie and Royle 2005). A conceptual understanding of the types of habitat used by the species and the factors that alter habitat suitability may be used to stratify habitat to improve sampling precision and ensure that key habitats within a region are sampled adequately. These considerations are also important in designing surveys to assert with a prespecified degree of confidence that a species is absent from a site (Wintle *et al*. 2012).

A substantial reduction of sampling error can be gained with rigorous standardisation of monitoring techniques (Sinclair *et al*. 2006). The use of protocols to produce data with less error and the better design and application of sampling techniques should result in a more robust outcome regarding the status of the bilby and efficacy of management. The aim of this paper is to describe the type of sign that should be detected to verify bilby presence with certainty as distinct from sign that can be used to flag possible presence. We also provide advice on the application of plot-based monitoring techniques to estimate the probability of bilby occupancy and detectability among habitat types within a region. The steps needed to sample habitat and assert absence are also described, including the use of aerial survey.

Bilby characteristics and habitat occupancy

Bilbies were once very widespread, occupying 70% of mainland Australia at the time of European settlement (Marlow 1958; Southgate 1990*a*; Friend 1990; Gordon *et al*. 1990; Johnson and Southgate 1990; Abbott 2001, 2008; Bradley *et al*. 2015). Bilbies are now restricted mostly to the northern section of their former range which consists predominantly of spinifex shrublands and woodlands. Less than 20% of their former range is currently occupied (Southgate 1990*a*; Bradley *et al*. 2015).

Bilbies are medium-sized burrowing marsupials, with breeding adults ranging in size from 0.6 to 2.5 kg (Johnson 2008; Menkhorst and Knight 2011). They are mostly nocturnally active, occupying a burrow during the day. Mature males are larger than females and have larger foraging ranges. Males commonly move 2–3 km between burrows per night whereas females move 0.5–2 km between burrows (Southgate and Possingham 1995; Moseby and O'Donnell 2003). They also have the propensity to emigrate and colonise habitat particularly in less productive parts of their range (Southgate and Carthew 2007; Southgate *et al*. 2007*a*).

A preliminary conceptual model describing the habitat types and the processes that influence the occupancy of habitat by the bilby has been developed (Southgate and Carthew 2007; Southgate *et al*. 2007*a*; Cramer *et al*. 2016). The model identifies that some habitat types such as residual landforms, palaeodrainage lines and brown clay plains remain more persistently suitable for occupation by the bilby than others such as sand plains and dune fields.

Sign needed to verify bilby presence

Track and gait characteristics

Fresh tracks are distinctive and can be used to distinguish the bilby from other species (Fig. 1*a*, *b*). The hind track imprints are narrow and longer than the front. The hind print is produced primarily by the fourth toe, with little conspicuous indentation caused by the short fifth toe. The toes and claws on the front foot produce three distinct parallel print marks of similar length (Fig. 1*c*). In comparison, rabbit (*Oryctolagus cuniculus*) tracks are rounded and the front and hind are of similar shape and size. Long- and short-nosed bandicoots (*Perameles* and *Isoodon* spp.) produce distinctive prints from the fourth and fifth toes on the hind foot and the toe and claw prints on the front feet are of uneven length. Finally, dasyurids and rodents produce a greater number of toe prints from the front and hind feet (Triggs 2004; Moseby *et al*. 2009). Bilbies move with a quadrupedal bounding overstep gait; the front imprints are staggered, and the hind imprints remain mostly parallel (Fig. 1*a*, *b*, *d*, *e*). The same gait pattern is produced consistently by several other similar-sized mammal taxa, including quolls, mulgara, bandicoots, rabbits and rats, and occasionally by some species such as brush-tailed possums (*Trichosurus vulpecula*). Consequently, clear track imprints showing three distinct parallel marks representing toes on the front foot (Fig. 1*c*) and slender hind foot marks without a distinct protruding side toe imprint (Fig. 1*d*, *e*) are considered necessary to confirm bilby presence. It is not sufficient to rely on gait pattern alone (Fig. 1*f*).

Food and diggings

Bilbies are omnivorous, consuming a range of invertebrates, including beetles, termites, and root-dwelling larvae, as well as plant material including seeds and bulbs (Southgate 1990*b*; Gibson 2001; Gibson and Hume 2004; Southgate and Carthew 2006; Navnith *et al*. 2009; Bice and Moseby 2013). Most food is obtained at the soil surface or by digging in the subsoil, and diggings are generally a conspicuous feature where bilbies have been foraging (Fig. 2*a*–*e*). Bilbies have been described as ecosystem engineers (James and Eldridge 2007; Read *et al*. 2008;

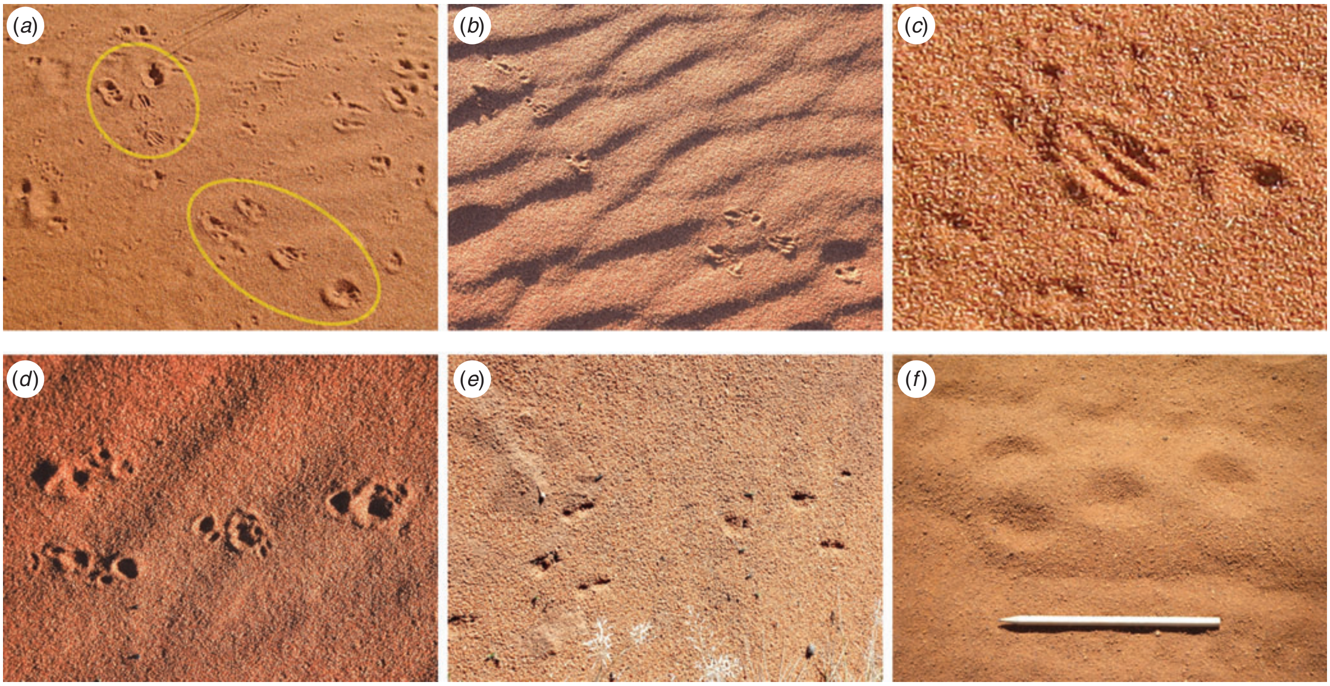

Fig. 1. Examples of clear bilby tracks showing the narrow hind foot often with indistinct fifth toe and front foot with three distinct parallel toe and claw marks of similar length: (*a*) bilby tracks among bird and hopping mice tracks; (*b*) clear fresh tracks across wind-blown sand; (*c*) close-up of the three distinct parallel marks of similar length that the toes and claws on the front foot produce; (*d*) unclear front foot imprints but narrow hind foot (showing the imprint of the 5th toe) in soft sand; (*e*) unclear front foot imprints but narrow hind foot (showing the imprint of the 5th toe) in hardened substrate; (*f*) example of gait pattern only – gait pattern alone cannot be used to verify presence conclusively.

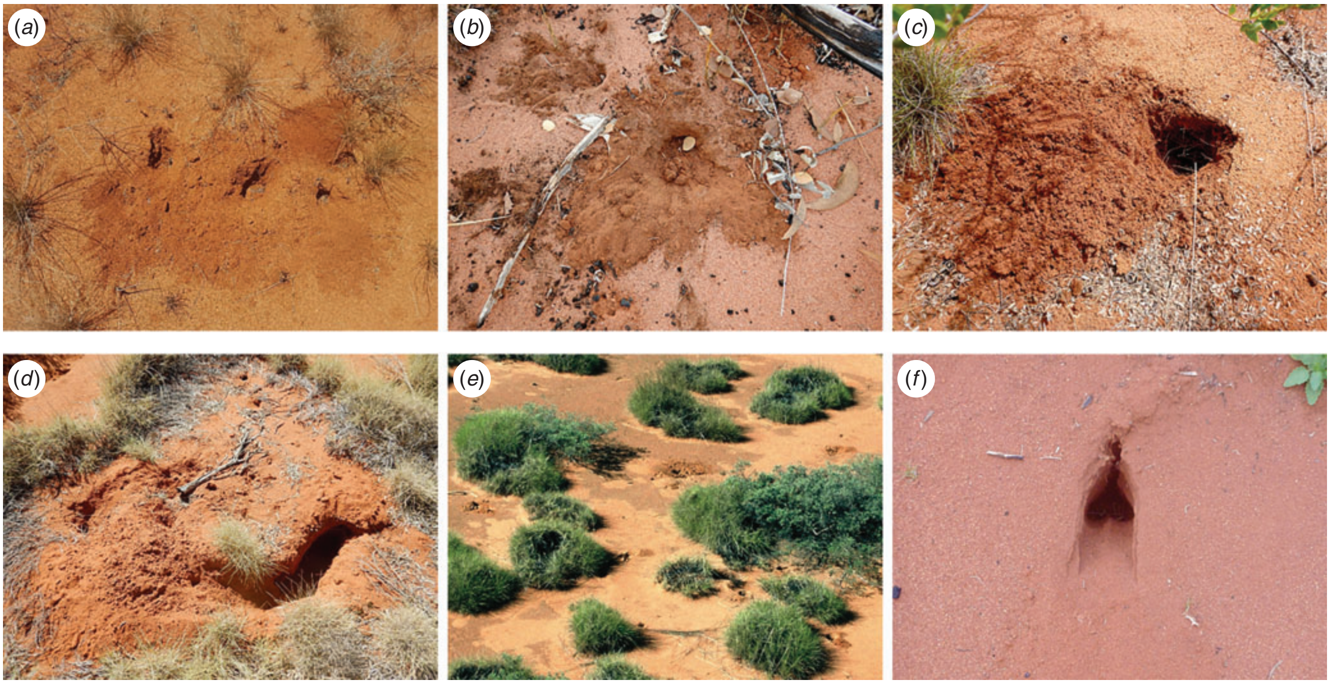

Fig. 2. Examples of bilby diggings in the open – these alone cannot be used to verify presence conclusively: (*a*, *b*) shallow diggings; (*c*) deep conical digging; (*d*) extensive diggings into termite nest; (*e*) aerial view of diggings along a palaeodrainage line; (*f*) varanid lizard digging – showing crescent shape often with mid-ridge.

Newell 2008; James *et al*. 2011; Chapman 2013; Fleming *et al*. 2014) because of the amount of digging and soil turnover they create. However, several other taxa, including varanid lizards, echidnas, rabbits, wallabies, bandicoots, mulgara and mice, can also produce bilby-like diggings (Moseby *et al*. 2009) while foraging (e.g. Fig. 2*f*). The only diggings that can be uniquely attributed to the bilby are those at the base of shrubs or forbs for root-dwelling larvae (Fig. 3). No other species extant in arid and semiarid Australia is known to expose and rip open plant roots containing larvae. A range of beetles and moths have larvae that spend part of their life history living within root structures in a range of shrub and forb species (Fig. 3*b*). Most of the plant taxa containing root-dwelling larvae used by bilbies are *Acacia* species (Table 1), and many of these are prevalent on residual landforms with stony or lateritic soils, e.g. *A. rhodophloia*, *A. hilliana*. Some of these shrubs are very broadly distributed (e.g. *Senna notabilis*) while others are more limited (e.g. *A. trachycarpa*). Diggings at the base of shrubs with roots torn open are usually obvious and numerous, and can remain evident for months and even years, especially if the substrate is stony and not easily eroded by water.

Faecal pellets (scats)

Bilby scats (Fig. 4) can be found most readily on top of or within the sand-spoil of diggings produced while foraging, and sometimes near burrows (Fig. 4*b–f*); they are rarely found away from some form of bilby digging activity. Typically, a group of 2–5 pellets is deposited, each pellet having a smooth coating and rounded ends. They are oblong shaped, longer than wide, and almost round in cross-section (Fig. 4*a*, *f*) as opposed to the more spherical rabbit scats (Triggs 2004; Moseby *et al*. 2009). The scats are firm and usually contain a mixture of sand, plant and invertebrate material (Southgate 1990*b*; Gibson 2001; Southgate and Carthew 2006) that can be discriminated relatively easily under low-power magnification (×10 power). Bilby scats can persist for several months, especially if buried within the spoil of a digging and there has been little rain. Faecal pellet diameter can be used to distinguish juveniles (Southgate 2005).

No other extant species in arid and semiarid Australia produces scats with these characteristics. Echidnas do not produce neat pellets and the ends are jagged where the longer extrusions break; their scats are usually dominated by ant and termite fragments, and plant material is rarely included. Similar-sized dasyurids do not produce scats with a comparable smooth coating and rounded ends. Some lizards and dragons, including the thorny devil (*Moloch horridus*), and frogs can produce pellets that have a smooth coating and can superficially resemble bilby scats. However, these scats are usually not encountered at diggings, generally contain little sand content, are relatively light and crumble easily, and white uric acid is sometimes present.

Burrow detection and use by bilbies

Bilbies construct burrows (Fig. 5*a–e*) that can be up to 4.5 m long and 2 m deep (Smyth and Philpott 1968). The burrows may or may not spiral downwards, can have side branches, and tunnels may be blocked by freshly dug soil (Smyth and Philpott 1968). The burrow entrances are round whereas the burrows of goannas and other reptiles are often crescent-shaped where the width is greater than the height. Most bilby burrows have a single entrance but 'aggregations' or 'warrens' with multiple burrow

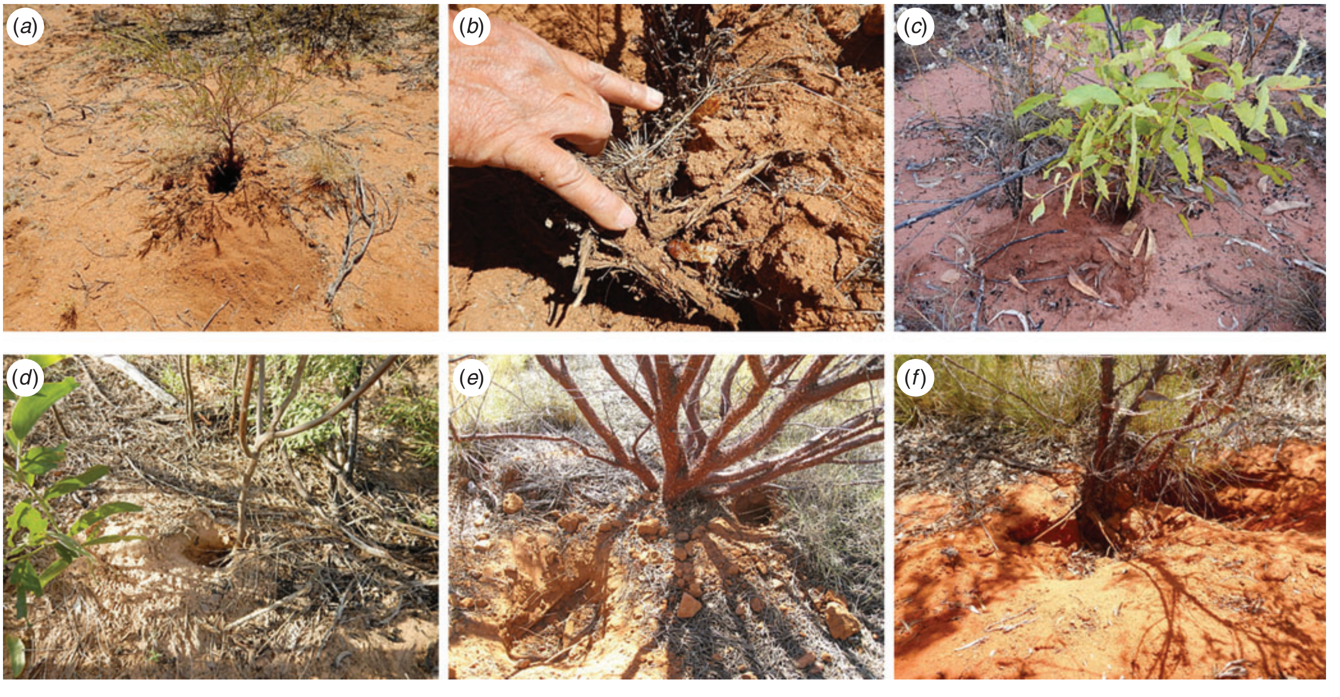

Fig. 3. Bilby diggings into the roots of shrubs that contain root-dwelling larvae: (*a*) *Acacia trachycarpa*, dwarf variety; (*b*) exuvia (pupal exoskeleton) of cossid moth larvae at the base and in roots of *A. trachycarpa* dwarf variety with bilby diggings; (*c*) *A. tumida*; (*d*) *Senna notabilis*; (*e*) *A.* aff. *grasbyi*; (*f*) *A. monticola*.

Table 1. Plant species known to contain root-dwelling larvae and used by bilbies as food

Bioregion abbreviations: AVW, Avon Valley Wheatbelt; CER, Central Ranges; DAL, Dampierland; DMR, Davenport Murchison Ranges; GAS, Gascoyne; GID, Gibson Desert; GVD, Great Victoria Desert; GSD, Great Sandy Desert; MUR, Murchison; PIL, Pilbara; TAN, Tanami; YAL, Yalgoo

Plant species	Larvae type	Location	IBRA Bioregion	Reference
Fabaceae				
Acacia spp.		Northam, WA	AVW	Gould (1863); Leake (1962)
		Queensland		Longman (1922)
Acacia acradenia	*Endoxyla* sp., Cossidae; Cerambycidae	Twin Bonanza mine, north-west Tanami	TAN	Liddle (2016); R. Paltridge and A. Schubert (pers. obs.)
A. acuminata	Cerambyx sp., Cerambycidae	Wheatbelt, WA	AVW	Whittell (1954); Jenkins (1974); Abbott (2001)
A. bivenosa	Cossidae	Pilbara, WA	PIL	M. Dziminski (pers. obs.)
		La Grange, WA	DAL	M. Dziminski (pers. obs.)
A. brachystachya		Warburton Ranges, WA	CER, GID, GVD	R. Southgate (pers. obs.)
A. colei	Cossidae	Pilbara, WA	PIL	M. Dziminski (pers. obs.)
		Dampier Peninsula, WA	DAL	G. Gaikhorst (pers. obs); M. Dziminski (pers. obs.)
		La Grange, WA	DAL	M. Dziminski (pers. obs.)
A. dictyophleba		Pilbara, WA	PIL	M. Dziminski (pers. obs.)
		Western Great Sandy Desert, WA	DAL, GSD	M. Dziminski (pers. obs.)
	Cossidae	Matuwa (Lorna Glen), WA	GAS, MUR	F. Morris (pers. comm.); M. Dziminski (pers. obs.)
A. effusifolia	Cossidae	Mount Gibson AWC Sanctuary, WA	YAL	M. Dziminski (pers. obs.)
A. eriopoda		Dampier Peninsula, WA	DAL	G. Gaikhorst (pers. obs)
A. aff. *grasbyi*	Cossidae	Matuwa (Lorna Glen), WA	GAS, MUR	M. Blythman (pers. comm.); M. Dziminski (pers. obs.)
A. hilliana		Tanami Desert, NT	TAN	R. Southgate (pers. obs); R. Paltridge and A. Schubert (pers. obs.)
		Northern Great Sandy Desert, WA	GSD	R. Southgate (pers. obs)
		Kiwirrkurra, WA	GID, GSD	R. Paltridge and A. Schubert (pers. obs.)
A. kempeana		Tanami Desert, NT	TAN	Johnson (1979); P. K. Kaltz (pers. comm.); R. Southgate (pers. obs.)
A. lysiphloia		Tanami Desert, NT	TAN	D. F. Gibson (pers. comm.)
	Endoxyla sp., Cossidae; *Maroga* sp., Xylorytidae and Cerambycidae	Twin Bonanza mine, north-west Tanami	TAN	Liddle (2016); R. Paltridge and A. Schubert (pers. obs.)
		Tennant Creek area	DMR	R. Paltridge and A. Schubert (pers. obs.)
A. melleodora		Kiwirrkurra, WA	GID, GSD	R. Paltridge and A. Schubert (pers. obs.)
	Cossidae	Pilbara, WA	PIL	M. Dziminski (pers. obs.)
A. monticola		Twin Bonanza mine, north-west Tanami	TAN	R. Paltridge and A. Schubert (pers. obs.)
		Western Great Sandy Desert, WA	DAL, GSD	M. Dziminski (pers. obs.)
		La Grange, WA	DAL	M. Dziminski (pers. obs.)
A. rhodophloia		Warburton WA	CER, GID, GVD	R. Southgate (pers. obs)
A. stellaticeps	Cossidae	Pilbara, WA	PIL	M. Dziminski (pers. obs.)
		Western Great Sandy Desert, WA	DAL, GSD	M. Dziminski (pers. obs.)
A. trachycarpa	Cossidae	Pilbara, WA	PIL	M. Dziminski (pers. obs.)
		La Grange, WA	DAL	M. Dziminski (pers. obs.)
A. trachycarpa – dwarf variant described in Maslin *et al*. (2010)	Cossidae	Pilbara, WA	PIL	M. Dziminski (pers. obs.)
A. tumida		Dampier Peninsula, WA	DAL	Ecologia (2015; 2016); M. Dziminski (pers. obs.)
		La Grange, WA	DAL	M. Dziminski (pers. obs.)
Indigofera georgei		Kiwirrkurra, WA	GID, GSD	R. Paltridge and A. Schubert (pers. obs.)
Senna artemisioides		Mount Gibson AWC Sanctuary, WA	YAL	M. Dziminski (pers. obs.)

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Table 1. (*continued*)

Plant species	Larvae type	Location	IBRA Bioregion	Reference
S. notabilis		Tanami Desert, NT	TAN	Liddle (2016); D. F. Gibson (pers. comm.); R. Paltridge and A. Schubert (pers. obs.)
		Kiwirrkurra, WA	GID, GSD	R. Paltridge and A. Schubert (pers. obs.)
		Dampier Peninsula, WA	DAL	M. Dziminski (pers. obs.)
		Pilbara, WA	PIL	M. Dziminski (pers. obs.)
S. oligophylla		Tanami Desert, NT	TAN	D. F. Gibson (pers. comm.)
S. venusta		Tanami Desert, NT	TAN	Johnson (1979)
Frankeniaceae				
Frankenia spp.		Tanami Desert, NT	TAN	K. Johnson (pers. comm.)
Eragrostis eriopoda	Lepidoptera	Warburton ranges, WA	CER, GID, GVD	Smyth and Philpott (1968)
E. laniflora	Lepidoptera	Warburton ranges, WA	CER, GID, GVD	Smyth and Philpott (1968)
Proteacea				
Grevillea refracta		Dampier Peninsula, WA	DAL	G. Gaikhorst (pers. obs)
Sapindaceae				
Dodonaea hispidula		Dampier Peninsula, WA	DAL	G. Gaikhorst (pers. obs)

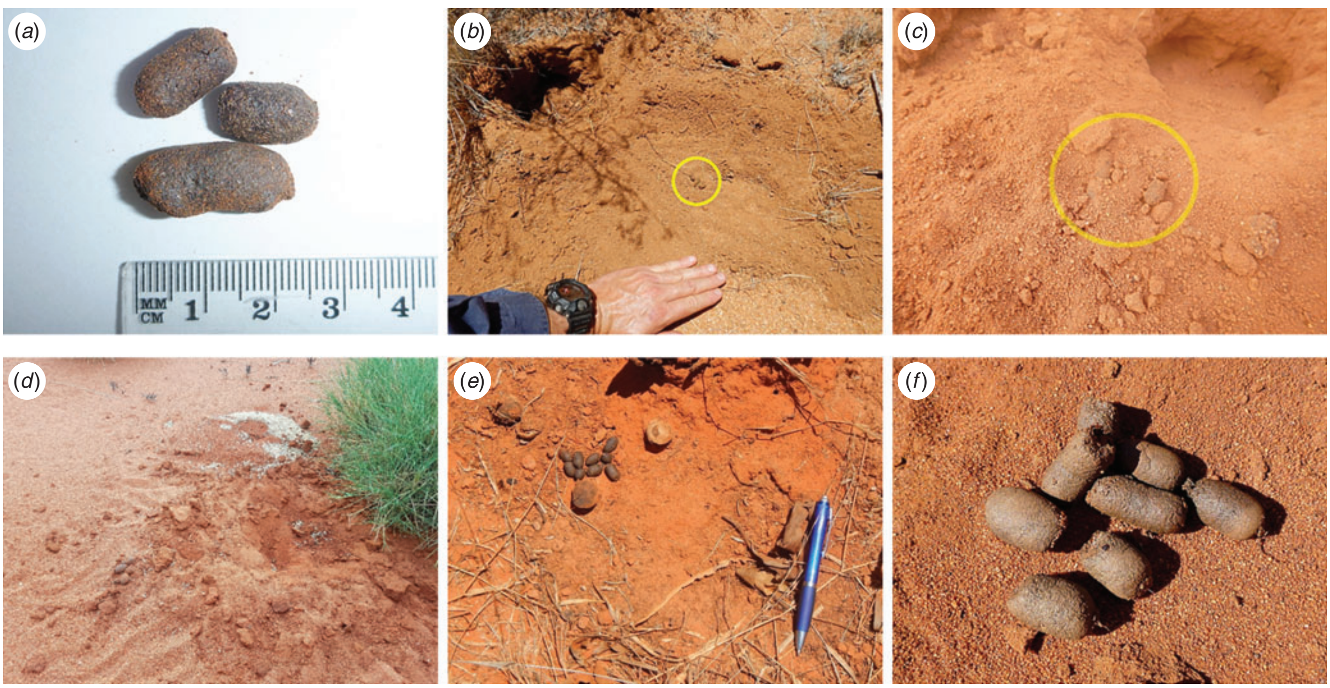

Fig. 4. Examples of bilby scats: (*a*) with scale; (*b*) scats are often found buried within the spoil of diggings; (*c*) partially hidden within the spoil of a digging; (*d*) on top of the spoil of a digging for ant eggs; (*e*) in the open; (*f*) close-up of a pile deposited in the open.

entrances (Fig. 5*f*) can occur (Southgate 1990*a*; Lavery and Kirkpatrick 1997). An apron of excavated sand is usually evident (Fig. 5*a–c*). However, the burrows are not always conspicuous and some burrow entrances can be hidden under logs (Fig. 5*d*) or termite mounds (Fig. 5*e*) and the reuse of old, seemingly inactive, burrows with inconspicuous or eroded (deflated) aprons can also occur (McRae 2004; R. Southgate pers. obs.). In addition, other species (e.g. cats, foxes, varanid lizards, echidnas, hopping mice and mulgara) can use or rework long-inactive bilby burrows and make them appear active (Read *et al*. 2008; Hofstede and Dziminski 2017).

Multiple separate burrows can usually be found within an established foraging area. The burrows are used at times during the night and during daylight hours for rest and refuge. A burrow is most often used by a single individual, but female and young, and occasional female–female or male–female sharing can occur. Repeat use of existing burrows is common, but the same burrow is infrequently used on consecutive days

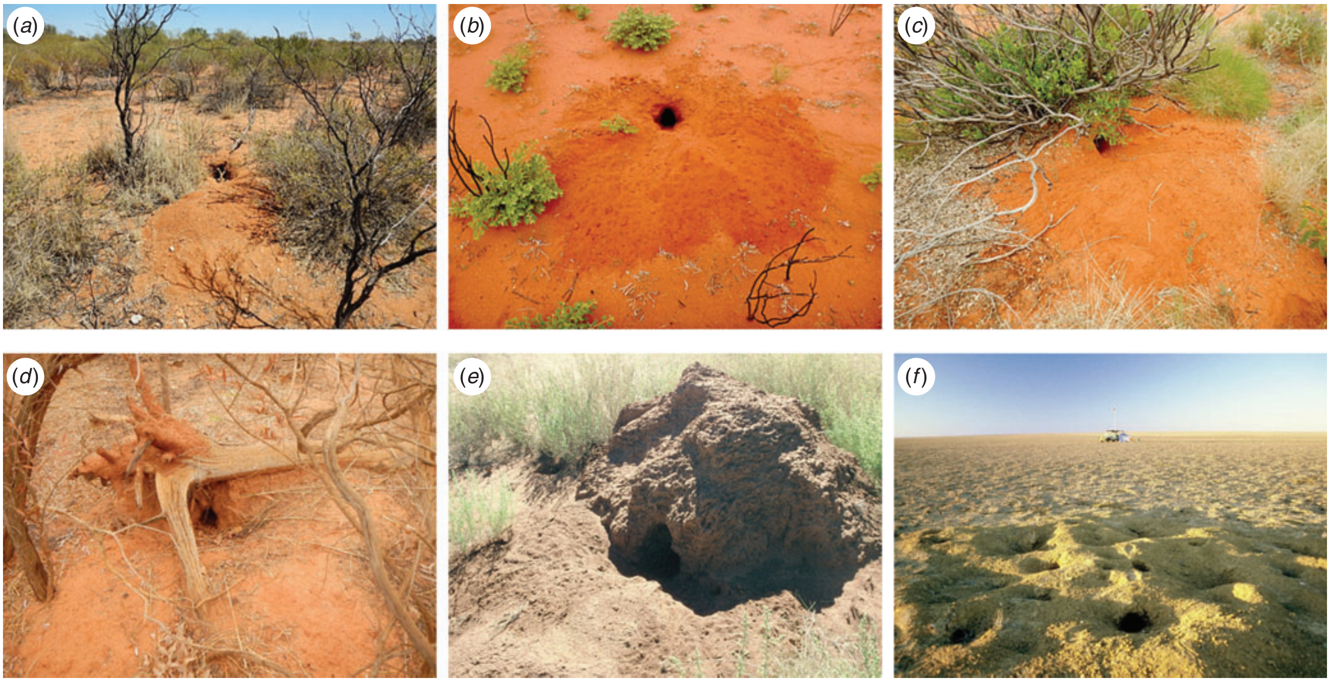

Fig. 5. Examples of active bilby burrows – these alone cannot be used to verify presence conclusively: (*a*) in *Acacia* shrubland; (*b*) open sand plain; (*c*) under a shrub; (*d*) old burrow under a log with a deflated sand apron; (*e*) burrow into the side of a termite mound; (*f*) 'Warren' system on brown clay soils in south-west Queensland.

and individuals can use up to 18 of these burrows concurrently over several months (Southgate and Possingham 1995; Moseby and O'Donnell 2003). Furthermore, an individual may visit and enter several burrows each night while foraging. Males have been recorded visiting more burrows than females in south-west Queensland (McRae 2004). Over time, new burrows are constructed, others are ignored and some eventually become abandoned (Lavery and Kirkpatrick 1997). Burrows may be scarce and difficult to find in recently colonised areas, sparsely distributed in some habitats (22 burrows km^{-2}: Smyth and Philpott 1968) or abundant in persistently occupied areas (hundreds of burrows km^{-2}: McRae 2004).

Consequently, we consider that bilby presence should not be based solely on the detection of bilby-like burrows because some burrows can be difficult to detect (potentially resulting in false-absence or omission error) and burrow use and refurbishment by a range of species can be misclassified as bilby activity (potentially resulting in false-presence error).

Systematic collection of sign to verify bilby presence and estimate regional occupancy

The bilby verification protocol (Table 2) describes the bilby sign that may be encountered in the field and provides a guide to systematically searching for the type of sign and information needed to validate bilby presence. The protocol should be applied while sampling a plot-based monitoring methodology such as the 2-ha plot technique (Moseby *et al*. 2009). This technique restricts both the area sampled and the search time to standardise the search effort and improve comparability of data among plots. However, other factors such as the skill of the observer, the suitability of the habitat to register sign or weather conditions before sampling can also affect whether a species is detected on a plot.

The plot-based monitoring applied in arid and semiarid Australia to monitor the bilby and medium-sized species in the past has been single application (Southgate *et al*. 2005, 2007*a*) and ignored imperfect detection. In this instance, sampling multiple plots once has provided an estimate of frequency of occurrence, which is a description of the surveyor's ability to *find* the species in the landscape, not where the species *is* in the landscape (MacKenzie and Royle 2005; Guillera-Arroita *et al*. 2014). To validly declare that a population has increased or decreased requires evidence that the change in extent, occupancy or abundance recorded was not attributable to a change in detectability (Wintle *et al*. 2012). Resampling of plots can be used to overcome this problem and to estimate the probability of detection (p) and the probability of the area occupied (psi) (MacKenzie *et al*. 2006). The repeat sampling needs to be conducted within a 'season' to meet the assumption that sites are closed to changes in occupancy for the duration of the repeat surveys. For bilbies, we recommend resampling plots within 1–3 months after the initial survey because of the potential for rapid growth of the population through reproduction (McCracken 1990; Southgate *et al*. 2000). Accurate aging of bilby sign is required to determine whether the activity encountered is fresh and to distinguish it from sign that may have been detected on previous samples. Similarly, it is important to age the sign of other species such as predators or competitors to enable an accurate comparison of occupancy among species of different size. The overlay sequence of the imprints of ubiquitous small animals including rodents,

Table 2. Protocol to assess potential bilby activity and verify bilby presence from sign
RDL, root-dwelling larvae

Sign	Significance	Recommended actions
Burrow or burrows located	Potential bilby activity. Presence not confirmed	1. Continue to search surrounding area for scats, clear tracks and multiple diggings into roots of RDL vegetation.[A] 2. Record dimensions of burrow circumference, photograph with scale, describe presence of apron and age since last activity.
Diggings located	Potential bilby activity. Presence not confirmed	1. Continue to search surrounding area for scats, especially within spoil of diggings, clear tracks, multiple diggings into roots of RDL vegetation.[A] 2. Record age and characteristics of diggings (e.g. identify what diggings are into – termites, spider burrows, seed stores of ants, etc.)
Unclear tracks (e.g. only gait pattern identified)	Potential bilby activity. Presence not confirmed	1. Continue to search surrounding area for clear tracks, scats, multiple diggings into roots of RDL vegetation.[A] 2. Measure the length and width of several track groups, photograph with scale. 3. Determine any other species responsible for tracks detected, estimate age of tracks.
Clear tracks (three distinct parallel marks from front feet identified, hind foot imprint narrow with indistinct side toes)	Presence confirmed	1. Record group width and length of several sets, assess if juveniles present (Southgate 2005), photograph with scale; estimate age of tracks. 2. For further confidence search surrounding area for scats, multiple diggings into roots of RDL vegetation.[A] 3. Record and describe any digging or burrow activity encountered.
Scats (commonly found hidden within spoil of diggings)	Presence confirmed	1. Collect several sets, store each set dry in separate paper bags or vials with silica gel beads and cotton wool; determine if juveniles present (presence of small pellets: Southgate 2005). 2. For further confidence, search surrounding area for clear tracks and multiple diggings for RDL. 3. Record and describe other digging or burrow activity encountered.
Multiple diggings into roots of RDL vegetation[A]	Presence confirmed	1. Identify plant species harbouring RDL, collect botanical specimen if uncertain for identification, assess age of diggings. 2. For further confidence, search for tracks and scats if diggings are fresh. If diggings are old, search surrounding area for other long-lasting sign: burrows, other diggings.

[A]Vegetation containing root-dwelling larvae that bilbies use as a food resource (commonly particular *Acacia* spp. – see Table 1).

dasyurids, birds, reptiles and invertebrates compared with the sign left by focal species can be used to gauge the age of sign and assess the plot conditions to retain sign.

Another major source of variation in sampling wildlife populations results from spatial variation of habitat (Pollock *et al*. 2002; MacKenzie *et al*. 2002). To provide estimates of regional occupancy, the sampling approach needs to provide inference about the entire area of interest and not only where the species is known to exist. This implies that careful consideration needs to be given to stratification of samples among key habitat types and that sufficient effort can be applied to adequately sample each habitat stratification. Because of the broad current and former distribution of the bilby, we cannot be certain that every habitat type has been described, particularly in parts of their former range or areas in their current range where little survey has been undertaken. Although survey effort can be focussed on habitat types that are known to support or be favourable for bilbies, other habitat types in a survey area should not be entirely excluded from sampling.

At a minimum, the stratification should endeavour to identify and include residual landforms (e.g. laterite rises) and habitat types where shrubs containing root-dwelling larvae are common; loamy or sandy soils associated with palaeodrainage lines and perched drainage lines that often harbour *Cyperus bulbosus*; and, sand plain and dune fields. Where fire is a regular and prominent part of the landscape, stratification should also include fire pattern with categorisation in terms of recent (1–2 years), medium (3–10 years) and old (>10 years) fire ages. Both fire and rainfall are key dynamic variables that can modify habitat suitability and food production (Southgate and Carthew 2006), and antecedent rainfall in 2-month increment periods for up to 12 months before sampling is useful to identify threshold conditions in production of key seed-producing species (Southgate and Carthew 2007). Rabbit, stock and predator (dingo/dog, red fox and feral cat) occupancy would ideally be captured to indicate the state of other important dynamic drivers of habitat suitability affecting food availability and predation pressure (Southgate *et al*. 2007*b*).

Estimating survey effort to assert bilby absence

Environmental impact statements commonly require observational data to assess whether or not a species is present within a survey area given that a certain amount of sampling effort has been applied. This information is used to determine the likely impact of habitat clearance or disturbance on the persistence of a species, assess potential mitigation measures or to identify offset requirements (Wintle *et al*. 2012).

McArdle (1990) developed a relationship to estimate the number of samples required to detect a species with a given level of scarcity or frequency of occurrence with a designated acceptable level of confidence that the species is absent. This level of confidence reflects a social and political judgement and the relative cost of asserting that the site is not occupied (i.e. 95% or 99% confidence). However, Wintle *et al*. (2012) have argued that it is not sufficient to consider only the detection probability and it is necessary to also take into account the expected prevalence of positive observations (expected rate of occupancy in a sample). They state that the number of samples to determine the status of a species at a site depends on the expected prevalence or base rate of occupancy for a species among different habitat types within the survey area, the reliability of a survey to detect a species using a standardised and repeatable technique, and the designated acceptable level of confidence that the species is absent.

If this approach is followed, the number of sequential non-detections necessary to be, say, 95% sure that the species is absent from a given site increases as the probability of occupancy for a particular habitat type increases. This reflects a common-sense understanding that if there is a strong prior knowledge that a species occupies an area, a substantially greater number of non-detections would be expected from the best known habitat to assert absence compared with the number of non-detections from more marginal habitat. Hence, the approach to survey an area for bilby sign should ensure that favoured habitat such as residual and fluvial land forms are adequately sampled and particularly areas with plant species known to harbour root-dwelling larvae and areas that have been burnt in the last 1–2 years need to be included (Table 1).

Single surveys of small-impact sites earmarked for clearing or development should also be extended to include a buffer area to account for the propensity of bilbies to emigrate and colonise habitat. Sampling within a buffer area of 8–10 km ($2 \times$ foraging range) around the perimeter of a proposed development site is needed to establish the proximity of any existing population and the likelihood that the impact site is important habitat and could be colonised. It also provides a regional context of the consequences of clearing habitat.

Aerial surveys

Aerial surveys using helicopters have proved effective for rapidly assessing bilby occurrence within a region and estimating discontinuity (Southgate *et al*. 2005; EcOz 2016). Digging and burrow activity can be readily detected along transects flown at a height of ~20 m and at 40 knots h^{-1}. The use of unmanned aerial vehicles or 'drones' should make this type of survey more cost effective and practical as the capacity of these devices improves. However, a process to estimate misclassification (false-presence) and omission (false-absence) error of the spatially flagged putative bilby digging and burrow sign is necessary with any form of aerial survey. When using a helicopter, sites where bilby-like burrow and digging activity have been flagged need to be verified either by ground visitation or 'hover checks' to determine whether activity was produced by the bilby or misclassified and created by another species. To determine omission error, a series of sites under the flight path, particularly in key favoured habitats such as laterite and sandy rises and drainage lines, needs to be examined. This reflects the approach to assert absence described by Wintle *et al*. (2012) and outlined above. Southgate *et al*. (2005) recorded 42% false-presence error and 3.2% false-absence error from ground-truth searches of 55 and 92 plots, respectively, sampled under the 1084-km flight path. EcOz (2016) reported that potential bilby sign was detected at 83 sites along a 490-km transect for a proposed pipeline. None was found to be bilby sign during 18 ground or 65 hover checks. Most of the misclassified sign was attributed to goanna burrowing activity. Furthermore, no bilby sign was detected at 44 2-ha plots used to sample favoured habitats to assess false-absence error (EcOz 2016). This approach provided compelling evidence that bilbies were absent from the survey area.

Discussion

The approach to survey medium-sized species has been lacking in arid and semiarid Australia, primarily because target species often occur at low densities and are difficult to observe (Edwards *et al*. 2004). Standardised pitfall and box-trapping techniques have been widely applied to monitor small mammals and reptiles (e.g. Hyder *et al*. 2010; Eyre *et al*. 2014) and aerial survey techniques to monitor large animals such as kangaroos, camels, donkeys and horses (e.g. Bayliss and Yeomans 1989; Southwell 1996; Cairns 1999) but no standardised approach suited to monitor co-occurring medium-sized animals has been applied. This has hampered our ability to address key questions regarding the status of threatened species like the bilby, and to investigate the causes for range decline (McKenzie *et al*. 2007; Woinarski *et al*. 2015). Only coarse-grained qualitative mapping of distribution of invasive species is available (West 2008) and this shows obvious discrepancies in estimation along state and territory boundaries. The absence of methodology is also evident in the protocols advocated by state and federal government to establish whether a species such as the bilby is present within a project area. For example, the federal guidelines (DSEWPaC 2011) recommend that 2 h search time be applied per 1-ha survey site for the detection of animal sign, then spotlight surveys focussed on burrows should be conducted to confirm bilby presence if required. We consider that it is unwarranted to apply this amount of search effort to detect bilby sign per hectare and cues to verify presence based on sign are not sufficiently explicit, resulting in an over-reliance on observation of individuals to confirm presence. Such guidelines encourage oversampling of small areas at the expense of gaining a better understanding of bilby detectability and occupancy within the regional context. The absence of a coherent protocol to assess bilby occurrence has also permitted the inclusion of ineffectual sampling activity to inflate the overall survey effort described to assert the absence of the bilby within a particular region (Southgate 2012).

The protocol we outline to detect and verify bilby sign plays a small but vital part in the approach to conduct broad-scale monitoring of bilbies at a landscape scale and to determine survey effort to assert absence. We also describe the importance of repeat sampling of plots and accurately aging sign to enable detection probabilities. The other important components are now largely in place, and these include:

A conceptual model linking key habitats and the processes affecting bilby distribution has been formulated (Southgate and Carthew 2007; Southgate *et al*. 2007*a*) and summarised in Cramer *et al*. (2016).

A standardised approach to collect presence/absence data has been developed and has now been widely applied (Southgate and Moseby 2008; Moseby *et al*. 2009; Paltridge 2016; Pedler *et al*. 2016). This technique can be used to monitor the bilby throughout its current distribution and a range of cohabiting native and introduced (threatening) species effectively.

Finally, a robust analytical approach developed in the early 2000s (MacKenzie *et al*. 2002; Tyre *et al*. 2003; Rhodes *et al*. 2011) can be applied to estimate occupancy and detection using presence/absence data.

These techniques have been applied extensively among a range of taxa and range of environments (e.g. Bailey *et al*. 2004; MacKenzie *et al*. 2006; Mattfeldt *et al*. 2009; van Strien *et al*. 2010). Resurvey over time enables the calculation of population rate of increase, argued by Hone and Buckmaster (2014) as the key parameter to describe population trend among regions or in response to a management program. Knowledge of occupancy among habitats within a region and the reliability of a technique to detect a species are also essential to determine survey effort necessary to assert absence of a species within a proposed development site in the order of several hundred hectares.

However, procedures to detect bilby sign accurately and efficiently are challenging. Skill is required to ensure that the species recorded are not misidentified and the age of sign is assessed accurately. Well trained and experienced observers are required to conduct sampling. While resampling of plots provides some opportunity to avoid the inclusion of unclear sign, good knowledge of the characteristics of imprints and sign produced by different species is required to make data collection effective. It is hoped that the protocol provided will help eliminate guess work, reduce propagation of false presence and absence error in field data and make decision making more defensible. The need for robust and defensible data is likely to become more acute if the species remains vulnerable to extinction and as pressure for development and disturbance of habitat increases.

Conflicts of interest

The authors declare no conflicts of interest.

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