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Predators in a mining landscape: Threats to a behaviourally unique, endangered lizard

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Abstract Patchy resource distribution can cluster predator activity around areas of the highest productivity in ecosystems. For the endangered Western Spiny-tailed Skink (*Egernia stokesii badia*) in Western Australia, the log piles that they permanently inhabit in an otherwise patchy, arid landscape, represent a potentially reliable, high abundance food source for predators. Not only are encounter rates by potential predators of *E. s. badia* likely to be influenced by vegetation structure at the microhabitat scale but also *E. s. badia* occurs in a region where mine sites and associated infrastructure, such as landfill sites, likely concentrate generalist predators (e.g. Feral Cats and corvids). We assessed the influence of the presence of coarse woody debris (CWD) and distance to the landfill on predator behaviour towards *E. s. badia* through plasticine model experiments, unbounded point count bird surveys and camera trapping. We found that CWD inhabited by *E. s. badia* attracted a greater relative activity of corvids compared with uninhabited CWD, or control sites without CWD. The relative activity of corvids and predatory birds combined increased with decreasing distance from the landfill. Preferential hunting by corvids at CWD inhabited by *E. s. badia* compared to both uninhabited CWD and open sites suggests that inhabited CWD may be targeted by generalist predators in the region, and that adaptive management may be required for species conservation around active mining areas.

Key words: *Egernia stokesii*, mitigation translocation, optimal foraging, predation, threatened species management.

INTRODUCTION

Predator–prey interactions can be influenced by the structure of the surrounding environment, which can both improve and reduce predation success, influencing either the ability of predators to catch prey or of prey to avoid predators (Heithaus *et al.* 2009; Schmidt & Kuijper 2015). For example, open spaces may improve the ability of prey to forage, but also increase their predation risk (Hernández & Laundré 2005; Hebblewhite & Merrill 2009; Rieucau *et al.* 2009). Alternatively, for predators, areas with the greatest quantity of prey may also have the lowest catchability (ease of prey capture; Hopcraft *et al.* 2005). Predators must, therefore, make a trade-off between hunting in areas where prey is more easily caught but are potentially less abundant and areas where prey encounter rates are highest but where their capture may be more challenging (Schmidt & Kuijper 2015).

As rainfall can be a major factor limiting ecological processes, ecosystems such as arid regions and deserts often have low primary productivity (Pianka 1967), plus a patchy distribution of resources (Aguiar & Sala 1999; McAllister *et al.* 2011). Predators are, therefore, likely to target areas of highest prey activity to optimise foraging; in arid landscapes this includes areas of higher productivity, such as watering holes, which attract congregations of prey (Valeix *et al.* 2010; Brawata & Neeman 2011). Many small to medium-sized animals rely upon log piles,

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Impact Statement: In a patchy semi-arid landscape, predators congregate around coarse woody debris (CWD), with predatory birds targeting CWD inhabited by Egernia stokesii badia.

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or coarse woody debris (CWD), as shelter, thermal refuges and as refuges from predators, particularly in Australian ecosystems (Chapple 2003; Sumner 2006; Jacobs *et al.* 2007; Christie *et al.* 2012). Indeed, CWD frequently harbours higher faunal abundance and diversity compared with surrounding habitats in a number of ecosystems (Loeb 1999; Lohr *et al.* 2002; Kappes *et al.* 2006; Craig *et al.* 2012). Many species reliant upon CWD have small home ranges (Sumner 2006; Christie *et al.* 2012), with some skinks travelling as little as 0–5 m per month (Sumner 2006).

The Western Spiny-tailed Skink (*Egernia stokesii badia*) is an endangered Australian lizard dependent upon CWD for long-term shelter and predator refuge (Pearson 2012). They produce latrine piles just outside inhabited logs (Lanham 2001), which may create a long-lasting olfactory cue to potential predators. This could make inhabited CWD even more attractive to potential predators of *E. s. badia* which use olfactory cues to hunt (Garrett & Card 1993; Hughes *et al.* 2010), such as Feral Cats, *Felis catus*, Foxes, *Vulpes vulpes* (Desmond & Chant 2001; Pearson 2012), snakes and varanid lizards (Arida & Bull 2008). The creation of adjacent communal latrines by *E. stokesii* and their behaviour of often spending their time at their core refuge site (Duffield & Bull, 2002) therefore potentially creates a more predictable target for predation. These skinks also do not employ predator-avoidance tactics that have been observed for other log-dwelling species, such as lizards that defecate distantly from their home crevices (Lanham 2001), or that are solitary (Chapple 2003). Instead, *E. s. badia* have keeled scales and highly spinose tails which are probably anti-predator adaptations, preventing the removal of the animal from crevices and hollows by predators (Arida & Bull 2008). The skinks are also highly cryptic, with a colour pattern camouflaging against the red earth of their open woodland habitat. The CWD supporting *E. s. badia* may, therefore, represent a high abundance, but low-detectability and low-catchability prey resource for their predators within the patchy, low-productivity heterogeneous landscape of the semi-arid Mid West region in Western Australia, in which the subspecies occurs.

In addition to small-scale habitat structures, such as CWD, influencing predator–prey dynamics, wide-scale habitat modification due to mining activity can also impact species interactions across the landscape. For example, the development of linear infrastructure including roads can act as predator highways and alter how introduced predators (such as Feral Cats and Foxes) utilise the landscape (Raiter *et al.* 2018). In addition to direct clearing for ore extraction, mining has multiplier effects on the degradation of the environment, such as general edge effects (Majer 2014; Cross *et al.* 2021). We predicted, therefore, that the encounter rate of predators, particularly introduced and generalist species (e.g. native corvids and introduced Feral Cats) with CWD will increase with decreasing proximity to the active mine site and associated infrastructure, in particular the landfill site. For this study, we hypothesized that in semi-arid open eucalypt woodland typical of the Mid West region of Western Australia, areas of highest abundance and lowest catchability primarily include fallen log piles (i.e. CWD). We predicted that the optimal hunting strategy of predators would be to target areas of highest abundance and lowest catchability and that predators would target CWD with olfactory cues marking occupancy. This translates to the prediction that predators would be more likely to hunt at sites occupied by *E. s. badia* than sites where individuals were not resident, and that predator encounter rates with CWD would be greater at log piles in closer proximity to the landfill. To test these predictions, we examined (i) if predators were more likely to actively hunt at inhabited CWD compared with uninhabited CWD or open sites (no CWD); (ii) if predator relative activity was higher at inhabited CWD, compared with uninhabited CWD or open sites; (iii) if dispersal behaviour by *E. s. badia* between areas of CWD was likely to significantly increase mortality risk; and (iv) if predator relative activity significantly increased with proximity to landfill. To gain a comprehensive understanding of the complex predator–prey dynamics within this system we employed three different sampling techniques: plasticine model experiments, unbounded point count surveys and camera trapping.

MATERIALS AND METHODS

Study area

The study area was within an iron ore mining tenement in the Mid West region of Western Australia (29°10′54.0"S, 116°32′55.1"E; Fig. A1). Available sites were limited by the location of inhabited CWD within eucalypt woodland of the arid to the semi-arid zone of the Mid West, and could be no more than 500 m from the access track (stretching approximately 45 km long east to west), due to logistical constraints. Inhabited and uninhabited CWD (confirmed by the presence/absence of a latrine pile) for the following studies were randomly selected from monitoring maps developed by the mine site environmental team and were of similar structure, generally a dead fallen tree with a number of hanging branches (Fig. 1). As the inhabited CWD ranged in length from approximately 7–20 m and height approximately 1–10 m, this variation was similarly captured in the selected uninhabited CWD.

Open sites (no CWD) were selected at random, also within 500 m of the track, and with similar vegetation to the sites with CWD. To identify the area in which we could

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Fig. 1. Examples of typical coarse woody debris (CWD) classified as uninhabited (a & b) and inhabited (c & d), by *Egernia stokesii badia* with the general structure of a single fallen dead tree, with numerous hanging branches and hollows/crevices.

safely work within OHS guidelines, a polygon shapefile of the area within 500 m of all vehicle-accessible tracks on the site was generated using the 'buffer' algorithm in QGIS. To avoid spatial autocorrelation with log piles, all identified log pile sites were also buffered by a distance of 100 m, again using the 'buffer' algorithm in QGIS, and then removed from the candidate area using the 'clip' algorithm in QGIS. Twenty points were then generated within the candidate area using the 'random points inside polygons' algorithm in QGIS. All random points were generated a minimum of 100 m apart, and ground-truthed to match the same open eucalypt woodland habitat surrounding the CWD sites.

Unbounded point count bird surveys

We used unbounded point count bird surveys to determine predator relative activity at sites with inhabited and uninhabited CWD, and open sites. We surveyed five inhabited CWD sites, five uninhabited CWD sites and five open sites (15 sites total), all at least approximately 100 m apart to ensure independent sampling points. Ten-minute unbounded point counts of potential predatory bird species (Table 1) were recorded at each site, repeated daily for 6 days, during spring 2018 (9th to 15th October) and again during autumn 2019 (2nd to 7th May). Each survey was preceded by a two-minute waiting period to avoid any disturbance influencing the survey outcomes. The order of sites visited was randomised each day to capture the range of bird activity times, from 07:00 to 17:00. For each recording, the same observer was situated at a count station and recorded the number of individuals per species detected (through either call or visual observation) in an unbounded direction. This method follows the widely used five-minute bird count method (Hartley 2012), extended for a further 5 minutes to increase the probability of detection.

Plasticine models

This experiment investigated the effect of skink position ('open', 'beneath vegetation' and 'exposed') and habitat

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Table 1. List of species considered potential *Egernia stokesii badia* predators recorded in bird surveys and observed on camera footage, with listed references supporting their known/likely previous predation upon lizards/reptiles

Predator species		Point count survey	Camera	Reference
Birds				
Australian Magpie	*Gymnorhina tibicen*	✗	✗	Veltman and Hickson (1989)
Black-breasted Buzzard	*Hamirostra melanosternon*	✗		Debus and Czechura (1992); Nunn and Pavey (2014)
Brown Goshawk	*Accipiter fasciatus*		✗	Aumann (1988); Aumann (1990)
Bush Stone-curlew	*Burhinus grallarius*		✗	Michael and Lindenmayer (2010)
Collared Sparrowhawk	*Accipiter cirrocephalus*		✗	Czechura *et al.* (1987)
Corvus sp.	*Corvus bennetti/Corvus orru/Corvus coronoides*	✗	✗	Stewart (1997); Stuart-Fox *et al.* (2003); Troscianko *et al.* (2008)
Grey Butcherbird	*Cracticus torquatus*	✗	✗	Walters (1980); Nordberg and Schwarzkopf (2019)
Grey Currawong	*Strepera versicolor*	✗	✗	Stapley (2004)
Grey Shrike-thrush	*Colluricincla harmonica*	✗	✗	Kutt and Kemp (1997); Baxter (2015)
Pied Butcherbird	*Cracticus nigrogularis*	✗		Michael and Lindenmayer (2010); Hansen *et al.* (2019)
Reptiles				
Sand Goanna	*Varanus gouldii*		✗	Pianka (1994); Cross *et al.* (2020)
Black-headed Monitor	*Varanus tristis*		✗	Pianka (1994); Cross *et al.* (2020)
Perentie	*Varanus giganteus*		✗	King *et al.* (1989); Pianka (1994)
Mammals				
Wild Dog/Dingo	*Canis lupus/Canis lupus dingo*		✗	Doherty *et al.* (2015); Doherty *et al.* (2019)
Feral Cat	*Felis catus*		✗	Pearson (2012); Stobo-Wilson *et al.* (2021)

selection (CWD *vs.* open sites) on predation frequency and severity (fatal *vs.* non-fatal). To assess predation pressure in relation to CWD, we created replica models of skinks simulating different behaviours, and placed them at sites with and without CWD. Plasticine models have been widely used to determine predation rates on reptiles (Vervust *et al.* 2007; Daly *et al.* 2008; Sato *et al.* 2014; Bateman *et al.* 2017). Our methods follow those of Wuster *et al.* (2004), Niskanen and Mappes (2005) and Sato *et al.* (2014), using non-toxic sculpting clay (Plastiplay; Brian Clegg, Rochdale, Lancashire, OL12 0HQ, UK), moulded to simulate the mean size, shape and general appearance of adult *E. s. badia*. Post-construction, models were coated with red dirt (retrieved on-site), to achieve approximate colouration of field specimens, increase the structural integrity of models by reducing the likelihood of clay softening and remove as much of the human scent as possible from the models.

The experiment followed a two-factor design, with five models per position: 'beneath vegetation' (under mid- or understorey vegetation cover), 'exposed' (on a live/dead branch or log surface) and 'open' (in open space), placed at five different CWD sites, and five models per position 'beneath vegetation' and 'open' at five separate open sites (due to the absence of CWD at open sites for 'exposed'). A total of 125 models were used. The positioning of models was limited by the habitat structure. Models in the 'beneath vegetation' position were placed beneath the cover of understorey vegetation where possible, and in the absence of understorey, under the lowest mid-storey cover available. 'Exposed' models were placed on living and dead branches, depending upon the nature of the CWD if part of the tree was still alive. The height of models placed on branches/logs varied from approximately 0.3–1.5 m from the ground. Models in the 'open' position were limited in range from the log pile from approximately 0.3–2.0 m, and were limited to the availability of shade, as at least partial shade was required to prevent the clay models from softening. The site types were defined as (i) CWD with a log pile similar to those inhabited by *E. s. badia* and (ii) open sites with no CWD present. CWD inhabited by *E. s. badia* were avoided to prevent encouraging predator activity.

Models were left out for over 7 days in winter/spring 2018 (23rd August to 1st September), and 6 days in autumn 2019 (11th to 17th April). Each model was checked daily and the following recorded: (i) if an attack occurred; (ii) where on the model any attack was evident; (iii) the form of predation (e.g. model removal or visible indentations); (iv) what predator made the attack (confirmed through camera trap records and comparison of peck/bite marks) and (v) the severity of the attack. Severity scores followed the definitions by Smithies (2016): (0) no attack; (1) non-fatal attack – light scratch/peck on back, tail or flipped with no markings and (2) fatal attack – deep wound on head or back, or model removed. Each model was smoothed after each daily recording to remove previous attack marks, and interactions with non-predatory species such as rodents were excluded. Corvid predators (*Corvus orru*, *Corvus bennetti* and *Corvus coronoides*) were combined as the single observation '*Corvus* sp.' (corvids) for this experiment as well as the unbounded point count surveys and camera recordings, due to the difficulty in differentiating peck marks and distant observations between corvid species.

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Camera traps

A single motion-activated camera trap (Reconyx Hyperfire 2 and Reconyx HC500) was placed at each of nine sites during the first survey in 2018 (three uninhabited, three open and three inhabited) and were placed at all sites (10 uninhabited, 10 open and 10 inhabited) during the second round of plasticine experiments and bird surveys in 2019. Cameras were attached to a metal fence post, facing south, depending on the presence of potential vegetation triggers which could activate the motion sensor. Cameras were placed approximately 10 m from each area of CWD and angled downwards to capture as much of the CWD as possible, as well as any animals moving on the ground in front of the camera. Camera images were used to identify the predator species responsible for model attacks. Not all models were able to be captured within the camera scope due to their placement around all sides of the CWD, and peck/bite measurements and shape were compared with other previous attacks to help identify the likely responsible predator.

Camera traps were used to determine the predator relative activity, diversity and hunting behaviour (actively hunting or not) at inhabited CWD sites, compared with both uninhabited CWD and open sites with no log piles. As species of *Egernia* are known to have a large range of mammal, reptile and bird predators (Chapple 2003), all vertebrates large enough to consume an adult or juvenile skink and that were known to hunt vertebrates were considered potential predators (Table 1). Overall, 30 cameras were placed at randomly selected inhabited CWD, uninhabited CWD and open sites. Sites were scattered randomly, between approximately 100 m and 46 km apart, due to the scattered pattern of *E. s. badia* colonisation of CWD within the area (Fig. A1). Sites were all selected within open eucalypt woodland habitats, to reduce variation between sites. Photos of potential *E. s. badia* predators were recorded between 20th August 2018 and 19th May 2020, with a total trapping effort of 16 057 days (approximately 385 000 h). Total trap nights for inhabited (5231), uninhabited (5499) and open (5327) slightly varied due to camera malfunctions, such as from water damage. SD cards were downloaded and batteries replaced in the field approximately every 3 months. Photos were analysed for behaviour using ethograms modified from a similar behavioural study (Meek *et al.* (2016): Table A1). Due to the low likelihood of capturing actual predation events on camera, assumptions of behaviour were based on predators within the camera view. Classification of potential 'active hunting' behaviour was surmised from the display of observation, movement and action responses listed in Table A1.

Data analysis

Analyses were conducted in the *R 4.04* statistical environment (R Core Team 2021). To determine whether the number of individual predatory birds recorded during unbounded point count surveys differed according to site type and distance to the landfill, we ran a generalised linear mixed-effects model (GLMM) with a Poisson distribution, in the package lme4 (Bates *et al.* 2011), with the number of individual predatory birds as the dependent variable, site type (uninhabited CWD, inhabited CWD and open sites) and distance to the landfill as the fixed effects and season (autumn or spring), site (replicates 1–5 of each site type) and day (1–6) as the random effects. Due to the scattered nature of sites (because of the natural variability in the availability of log piles), distance to the landfill was a continuous variable. This analysis was repeated for the number of corvids observed according to site type and distance to the landfill.

To determine whether differences in the number of fauna attacks on plasticine models (dependent variables) varied according to site type (uninhabited CWD and open sites), model position ('beneath vegetation', 'open' and 'exposed'), and distance to the landfill, we used a GLMM with the number of fauna attacks on plasticine models as the dependent variable, site type (uninhabited CWD and open sites), model position ('beneath vegetation", 'open' and 'exposed') and distance to the landfill as the fixed effects and site (five sites per CWD or open site type), day surveyed (as the surveys were conducted over a week) and season (spring and autumn) as the random effects. To determine if the severity of plasticine model attacks varied according to site type, we used a Wilcoxon rank-sum test with attack severity as the ordinal dependent variable and site type (uninhabited CWD *vs.* open sites) as the independent variable.

To explore whether the number of predators recorded on cameras differed according to site type and distance to the landfill, we ran a GLMM with a Poisson distribution, with the number of predators (reptiles, mammals and birds combined) as the dependent variable (adjusted to a relative abundance index, the number of sightings per 100 trap nights), site type (uninhabited CWD, inhabited CWD and open sites) and distance to the landfill as the fixed effects and site (replicate) as the random effect. We then repeated this analysis on the number of mammals alone, birds alone, reptiles alone, then corvids alone and Feral Cats alone, in five separate GLMMs.

To assess whether the proportion of predators detected on camera traps that (i) actively hunted and (ii) did not actively hunt, differed according to site type, we calculated the proportion of predator sightings that exhibited potential active hunting behaviour at each site, and analysed these data using a Kruskal–Wallis rank-sum test with site type (uninhabited CWD, inhabited CWD and open sites) as the independent variable. If there was a significant effect on site type, we used a post-hoc Dunn test to determine between which site types there was a difference. We ran this analysis for bird predators (all species combined), Feral Cats alone (42 sightings) and corvids alone (80 sightings). The latter two categories were the two predator taxa with large enough sample sizes to separately compare potential hunting activity at different site types.

RESULTS

Predator relative activity

Unbounded point count surveys found predatory bird relative activity to vary with site type, with more

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predatory birds found at inhabited CWD compared to open sites ($z = 2.59$, $P = 0.010$). However, differences between inhabited and uninhabited CWD were non-significant ($z = -1.87$, $P = 0.061$; Fig. 2a). Predatory bird relative activity did not differ between uninhabited CWD and open sites ($z = 0.86$, $P = 0.391$). The mean number of predatory birds observed also decreased with increasing distance from landfill ($z = -3.25$, $P = 0.001$). Unbounded point count surveys also found corvid relative activity to vary with site type, with more corvids found at inhabited CWD compared to both uninhabited CWD ($z = -128.8$, $P < 0.001$) and open sites ($z = -142.6$, $P < 0.001$), and more corvids at uninhabited CWD than open sites ($z = 13.76$, $P < 0.001$; Fig. 2b). The mean number of corvids observed also decreased with increasing distance from landfill ($z = -147.9$, $P < 0.001$).

The overall relative activity of predators (bird, mammal and reptile predators combined; Table A4) captured on cameras did not differ between inhabited CWD and either uninhabited CWD ($z = 0.57$, $P = 0.572$) or open sites ($z = -0.99$, $P = 0.322$), or between uninhabited CWD and open sites ($z = -0.43$, $P = 0.667$) nor with distance to the landfill ($z = -0.14$, $P = 0.886$). Neither the number of predatory mammals, predatory birds, predatory reptiles, Feral Cats nor number of corvids (separately) differed between inhabited CWD, uninhabited CWD and open sites and none showed any relationship with distance to the landfill (Table A2).

Attack rates on lizards

The number of attacks on the plasticine models did not differ according to the presence or absence of CWD ($z = 0.08$, $P = 0.936$), or distance to the landfill ($z = -0.29$, $P = 0.936$). Model position also had no effect, with no difference between the number of predator attacks on 'open' models compared with 'exposed' ($z = 0.65$, $P = 0.514$) or 'beneath vegetation' models ($z = 0.67$, $P = 0.501$), and no difference between attacks on 'exposed' compared with

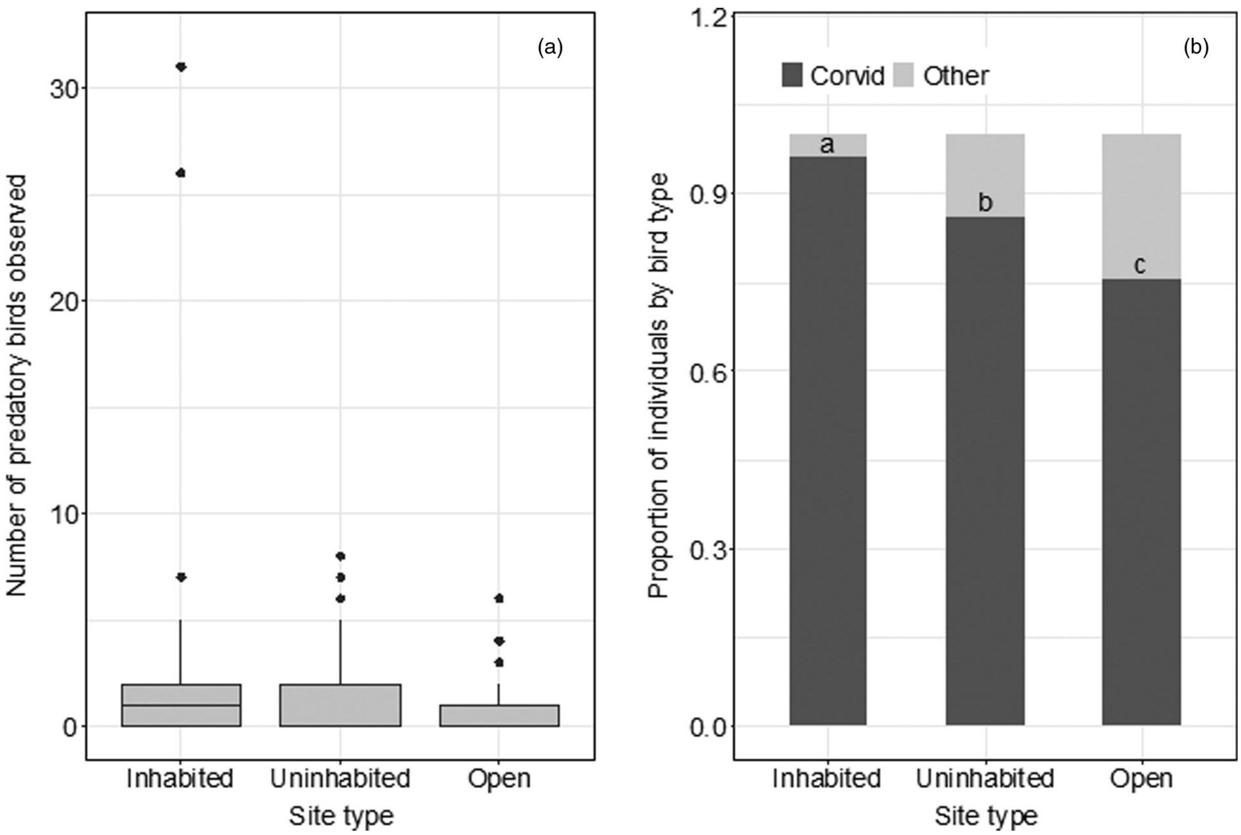

Fig. 2. (a) The number of predatory bird sightings at coarse woody debris (CWD) inhabited by *Egernia stokesii badia*, CWD uninhabited by *E. s. badia*, and open sites and (b) the proportion of predatory bird sightings that were corvids (dark grey) and other (pale grey; Grey Butcherbirds, Grey Shrike Thrush, Pied Butcherbirds and Black-breasted Buzzards combined), observed at CWD inhabited by *E. s. badia*, CWD uninhabited by *E. s. badia* and open sites. Bird sightings were recorded from unbounded point count surveys, pooled across autumn and winter survey events.

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'beneath vegetation' models ($z = 0.16$, $P = 0.246$; Table A3). The attack severity on plasticine models also did not vary according to site type ($W = 316\ 409$; $P = 0.887$).

Predator behaviour

The proportion of predators exhibiting potential active hunting behaviour did not differ between site types ($H_2 = 4.73$, $P = 0.094$). However, the proportion of combined avian predators actively hunting was found to differ between site types ($H_2 = 6.49$, $P = 0.039$), with a greater proportion of birds actively hunting at inhabited CWD compared to open sites ($Z = 2.53$, $P = 0.011$). There was no difference in the proportion of birds actively hunting at inhabited compared to uninhabited CWD ($Z = 1.09$, $P = 0.276$; Fig. 3) or at uninhabited CWD compared to open sites ($Z = -1.41$, $P = 0.160$).

The difference in the proportion of Feral Cats exhibiting potential active hunting behaviour at different site types was non-significant ($H_2 = 4.76$, $P = 0.092$). A Feral Cat was also recorded capturing an adult *E. s. badia* on our cameras on one occasion (Fig. 4). The proportion of corvids actively hunting did differ between site types ($H_2 = 7.04$, $P = 0.030$), where more corvids actively hunted at inhabited CWD, compared to both uninhabited CWD ($Z = 2.18$; $P = 0.029$) and open sites ($Z = 2.49$; $P = 0.013$), and no difference was found between uninhabited CWD and open sites ($Z = -0.44$; $P = 0.662$).

DISCUSSION

The plasticine model study and the presence of predators recorded during the camera trap survey failed to produce significant results or details on predator relative activity or behaviour, due to the low capture rate of individuals and abundance of zeros in the data. This study, therefore, highlights the value of a multi-faceted approach to understanding predator behaviour and predator–prey dynamics, as, in isolation, these two survey methods failed to reveal any

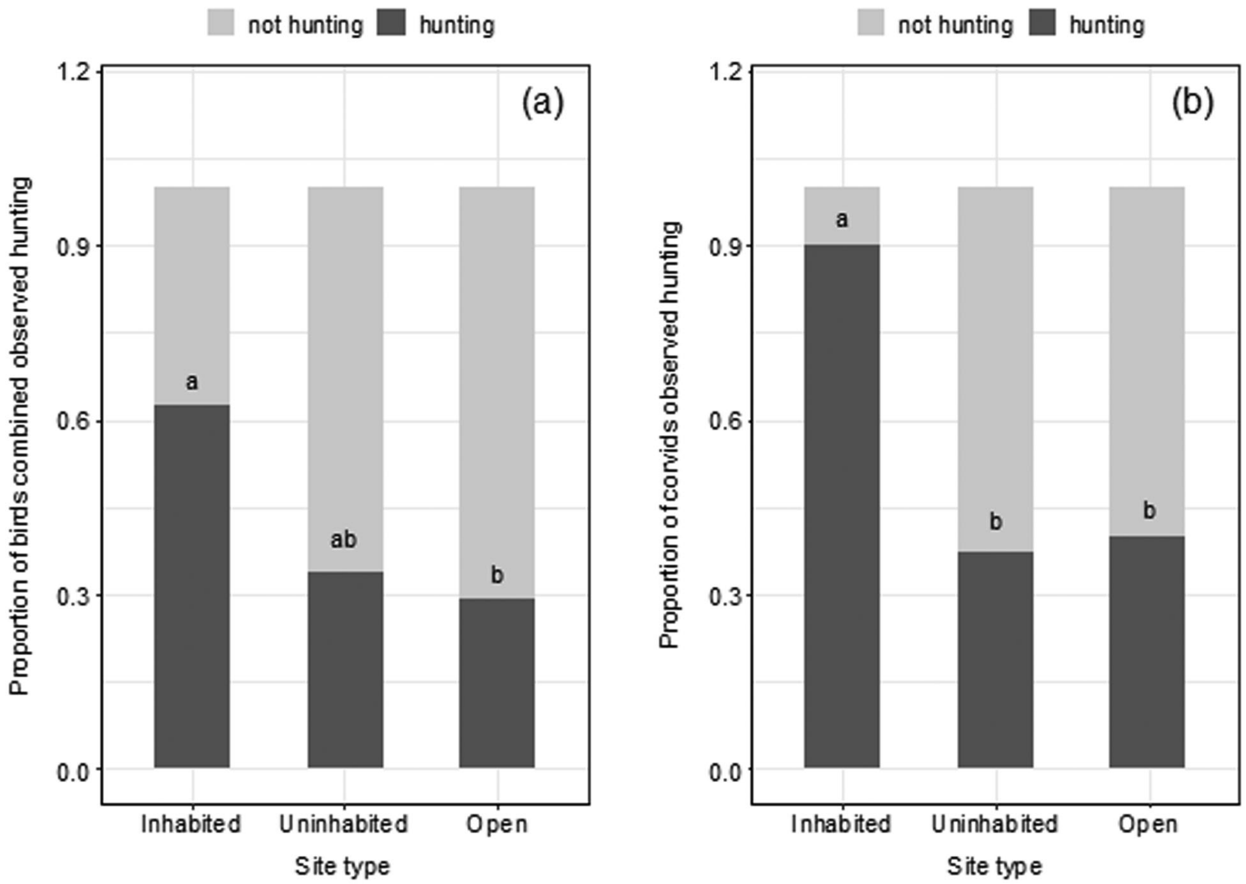

Fig. 3. The proportion of (a) combined bird predators and (b) corvids classified as hunting (dark grey) or not hunting (pale grey) when visiting coarse woody debris (CWD) inhabited and uninhabited by *Egernia stokesii badia*, as well as open sites, as observed on camera trap recordings. Black letters above bars indicate significant differences ($P < 0.05$).

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Fig. 4. Camera trap image of a Feral Cat (centre) at coarse woody debris with an adult *Egernia stokesii badia* in its mouth.

significant patterns. Sample sizes are nearly always an issue in ecology, particularly when targeting scarce apex predators (e.g. Feral Cats) in a low productivity arid zone in an El Niño-Southern Oscillation (ENSO) dominated, highly variable climate such as the Mid West of Western Australia. However, supplementing the study with the addition of unbounded point count surveys and behaviour analysis of camera trap images enabled observation of significant patterns in predator behaviour and relative activity, providing an important insight into the predation risk for *E. s. badia*.

The greater relative activity and exhibition of potential hunting behaviour of corvids at sites with inhabited CWD compared to other sites supports the hypothesis that some predators may actively target CWD containing long-term group-living reptile colonies, potentially due to the appeal of a high abundance, reliable food source. The hypothesis that CWD acts as a greater focus for predators than the open landscape surrounding them was partially supported, with the observed higher rate of active hunting and relative activity of predatory birds at inhabited CWD compared with open sites. These results support previous literature suggesting CWD are sites of high species activity (Loeb 1999; Lohr *et al.* 2002; Kappes *et al.* 2006; Craig *et al.* 2012) and, therefore, potentially centres of activity for predators in a patchy heterogeneous landscape.

Egernia stokesii badia live in a heterogeneous matrix of *Acacia*-dominated shrubland and open eucalypt woodland (Pearson 2012). Such a patchy landscape gives an advantage to predators that can travel long distances in short amounts of time (Valeix *et al.* 2011; Carter *et al.* 2012; McGregor *et al.* 2016), and are able to target certain habitat patches for improved hunting success (Shettleworth *et al.* 1988; Doniol-Valcroze *et al.* 2011; Schmidt & Kuijper 2015). The most frequent predators seen at all site types over the 2 years of camera trapping were Feral Cats and corvids, both generalist predators (Dickman 1996; Piper & Catterall 2006; Fielding *et al.* 2020). Both Feral Cats (Moseby *et al.* 2009; McGregor *et al.* 2017), and corvids (Rowley, 1973) have been observed travelling large distances to forage.

Corvids were also abundant across the landscape. As a visually oriented predator (Stuart-Fox *et al.* 2003), they were responsible for all attacks on plasticine models, and were the most abundant predatory bird at all site types, especially at inhabited CWD. Corvids, including the Little Crow, *Corvus bennetti* (Stuart-Fox *et al.* 2003) and the Australian Raven, *C. coronoides* (Stewart 1997) attack lizards (Troscianko *et al.* 2008), and our results are consistent with recorded attacks by Australian Ravens on models imitating the Rottnest Island Bobtail (*Tiliqua rugosa konowi*), a lizard of similar size (~27 cm in length) to *E. s. badia* (Oversby *et al.* 2018). Australian Ravens have also been observed attacking and feeding on the tails of live Australian Water Dragons (*Physignathus lesueurii*), almost 1 m in length (Pérez 2013). The Little Crow is also one of the main predators of Rock Dragons (e.g. *Ctenophorus decresii*), an agamid with an SVL of approximately

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78 mm (Stuart-Fox *et al.* 2003). Consistent with these previous reports, and the observed high relative activity of corvids in proximity to inhabited CWD, *E. s. badia* are likely a component of the corvid diet.

Although *C. bennetti, C. orru* and *C. coronoides* are native to the study area, corvid populations have been found to increase in or around human settlements and modified landscapes, such as landfills (Marzluff *et al.* 2001; Coates & Delehanty 2004; Preininger *et al.* 2019), as was found in this study. Corvids are known to travel tens of kilometres to access anthropogenic food sources within modified landscapes (Marzluff & Neatherlin 2006), and anecdotal records from 2004 to 2020 show that *C. bennetti*, in particular, were scarce in the area until the construction of the landfill site (M. Bamford per. obs., 2021). As with introduced fauna, overabundant synanthropic species also negatively impact native species through different mechanisms such as disease and predation (Côté *et al.* 2004; Peery & Henry 2010) and can cause devastating impacts on less adaptable, rarer species (Garrott *et al*, 1993). The global pattern of population expansion by some corvids is of particular concern (Jerzak 2001; Marzluff *et al.* 1994; Storch & Leidenberger 2003), as they threaten less abundant native species through predation (Marzluff *et al.* 1994; Peery & Henry 2010). An overabundance of corvids within a landscape of anthropogenic disturbance, therefore, risks the suppression and decline of sympatric rarer, less adaptable species such as *E. s. badia*.

Feral Cats have been suggested as a potential threat to *E. s. badia* populations in the past (Desmond & Chant 2001), particularly to juveniles (Pearson 2012), and a range of anecdotal evidence indicates they may be one of the skinks' main predators (Lee-Steere 2008). Reptiles in general are a significant proportion of the Feral Cat diet (Dickman 1996; Paltridge *et al.* 1997; Doherty *et al.* 2015; Woinarski *et al.* 2018), particularly medium-sized reptiles (Stobo-Wilson *et al.* 2021). Although Feral Cats were not found to actively target CWD, their capacity to hunt adult (as well as the smaller juvenile) skinks was confirmed through camera trap imaging. Therefore, the conclusion that Feral Cats do not target or alter their behaviour according to the presence of skink colonies or CWD must be interpreted with caution as, whilst untargeted, their suppressive effect may still be significant.

As well as identifying the predators of the apparent greatest threat to *E. s. badia*, we also explored differences in the behaviour of these predators at different sites. As group-living and scale morphology of *E. s. badia* are potentially adaptive in offsetting high predator activity at CWD, dispersal away from the CWD was predicted to be the riskiest activity for *E. s. badia* to undertake. However, there was no difference observed in the prevalence or severity of predator attacks in the plasticine model study according to their position of 'open', 'beneath vegetation' or 'exposed'. Nonetheless, this result needs to be interpreted with caution. We only definitively identified corvids attacking our models and although identification of individual corvids was not possible, it appeared as though, once a detection was made, corvids revisited the same site on multiple days to attack models. Similar corvid behaviour has been observed in other studies, where the design of baits and traps required altering to avoid the repeated incidental capture, or disturbance by corvids (Matlack *et al.* 2006; Way 2009; Page *et al.* 2013). Therefore, whilst this study found no trends in attack rate or severity according to model placement, we recommend further testing to understand the level of risk associated with dispersal by *E. s. badia* individuals, particularly in the context of future translocations.

CONCLUSION

Understanding predator–prey interactions is likely critical to informing the management and conservation of *E. s. badia* populations occurring in mining tenements. Management effort to ameliorate the loss of skink populations through mining activity will likely occur, in part, in the form of mitigation translocations. Our study suggests that predator control is likely to be important for translocation success. Two identified predators in this investigation, Feral Cat and corvids, are attracted to explore novel objects and sites (Church *et al.* 1994; Heinrich 1995; Bradshaw *et al.* 2000; Reina 2010; Miller *et al.* 2015), such as translocation sites. As high mortality of individuals is often observed immediately post-translocation likely due to an unfamiliarity with the surroundings (Letty *et al.* 2000; Pinter-Wollman *et al.* 2009), and reptiles often move large distances and exhibit homing behaviour post-relocation (Germano & Bishop 2009), translocated skinks are likely to be more at risk from predator attacks. Our results suggest that the control of predators, including introduced predators, may be important to facilitate the success of future translocations of the endangered *E. s. badia*.

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AUTHOR CONTRIBUTIONS

Holly Sydelle Bradley: Conceptualization (equal); data curation (lead); formal analysis (equal); investigation (lead); methodology (equal); project administration (lead); writing – original draft (lead); writing – review and editing (lead). **Michael D Craig:** Conceptualization (equal); formal analysis (equal); investigation (supporting); methodology (equal); supervision (equal); writing – review and editing (equal). **Sean Tomlinson:** Conceptualization (equal); formal analysis (equal); methodology (supporting); supervision (equal); writing – review and editing (equal). **Adam Cross:** Conceptualization (equal); methodology (supporting); supervision (equal); writing – review and editing (equal). **Mike Bamford:** Conceptualization (equal); methodology (supporting); supervision (equal); writing – review and editing (equal). **Philip W Bateman:** Conceptualization (equal); investigation (supporting); methodology (equal); supervision (lead); writing – review and editing (equal).

CONFLICT OF INTEREST

The authors declare the following financial interest/relationship: MB has worked as a consultant for the mining company where this research took place, although this work was separate from the research included in this study.

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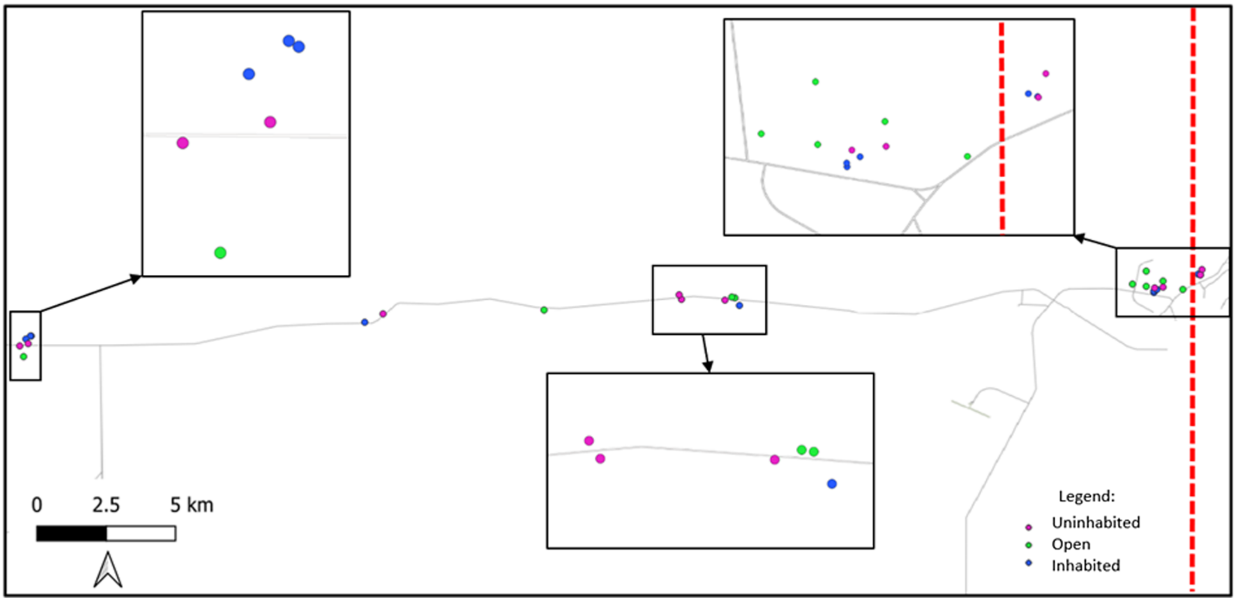

Fig. A1. Map of the location of all 30 camera traps, including 10 uninhabited coarse woody debris (CWD) (pink), open sites with no CWD (green) and inhabited CWD (blue). The red dotted line represents distance zero (the location of the landfill, from which the distance of sites is recorded). Grey lines represent major tracks.

Table A1. Ethograms of the possible quantitative behaviours of potential *Egernia stokesii badia* predators were recorded on camera traps when considered potentially 'active hunting'. Predators exhibiting any of the observe/move/act responses were classified as potentially 'actively hunting'. CWD, coarse woody debris

Predator type	Observe response	Move response	Act response
Mammals, reptiles and birds	Look/stare at ground, CWD or model bait	Move towards model bait or CWD/through open space, stalking	Looks down (and sniffs if a mammal) towards the ground or log surface, investigates log or ground surface, attacks model bait or prey item

Table A2. Summary of generalized linear mixed-effects analysis of the effect of site type and distance to the landfill on the number of predatory animals. Shown are the values of the *z* statistic and their corresponding *P*-values. CWD, coarse woody debris

	Inhabited *vs.* uninhabited CWD		Inhabited CWD *vs.* open		Uninhabited CWD *vs.* open		Distance to landfill	
Variable	*z*	*P*	*z*	*P*	*z*	*P*	*z*	*P*
Predatory mammals	0.06	0.949	−0.59	0.558	0.59	0.558	−0.70	0.482
Predatory birds	0.62	0.536	0.87	0.387	−0.26	0.799	0.29	0.774
Predatory reptiles	0.61	0.539	0.57	0.568	0.06	0.951	−0.42	0.678
Feral Cats	0.20	0.839	−0.71	0.479	−0.52	0.605	−0.06	0.950
Corvids	1.01	0.315	−1.02	0.310	−0.01	0.992	−0.09	0.930

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Table A3. Summary information of the total number of models attacked per model position ('beneath vegetation', 'open' and 'exposed on log'), in each treatment (sites with and without logs) and the proportion of days each model was found attacked, out of the available 325 days

Treatment		Model position					
		Beneath vegetation		Open		Exposed on log	
Site type	Severity	Total	Proportion	Total	Proportion	Total	Proportion
Log	0	313	0.96	306	0.94	303	0.93
	1	3	0.01	10	0.03	11	0.03
	2	9	0.03	8	0.02	11	0.03
No Log	0	307	0.94	302	0.93		
	1	7	0.02	12	0.04		
	2	11	0.03	11	0.03		

Table A4. The number of sightings per predatory species observed on camera trap footage during the trapping period, at coarse woody debris (CWD) inhabited by *Egernia stokesii badia*, CWD uninhabited by *E. s. badia* and sites with no CWD

Predator	Species name	Number of individuals observed		
		Inhabited	Uninhabited	No CWD
Australian Magpie	*Gymnorhina tibicen*	4	6	6
Bush Stone Curlew	*Burhinus grallarius*	0	0	1
Brown Goshawk	*Accipiter fasciatus*	1	1	0
Corvid	*Corvus sp.*	10	40	29
Feral Cat	*Felis catus*	9	12	20
Grey Butcherbird	*Cracticus torquatus*	2	3	2
Grey Currawong	*Strepera versicolor*	3	7	8
Grey Shrike Thrush	*Colluricincla harmonica*	4	0	0
Sand Goanna	*Varanus gouldii*	0	0	3
Black-headed Monitor	*Varanus tristis*	0	4	1
Perentie	*Varanus giganteus*	1	1	0
Wild Dog/Dingo	*Canis lupus/Canis lupus dingo*	6	5	5

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