

## Corrigendum to: Where there's smoke, there's cats: long-unburnt habitat is crucial to mitigating the impacts of cats on the Ngarlgumirdi, greater bilby (*Macrotis lagotis*)

Harry A. Moore, Yawuru Country Managers, Bardi Jawi Oorany Rangers, Nyul Nyul Rangers, Nykina Mangala Rangers, Lesley A. Gibson, Martin A. Dziminski, Ian J. Radford, Ben Corey, Karen Bettink, Fiona M. Carpenter, Ruth McPhail, Tracy Sonneman and Bruce Greatwich

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The Indigenous translation of the short summary for this paper, as well as the short summary itself and the explanation of the translation, was inadvertently missing from the published version of this paper. This should have been included as below:

### SHORT SUMMARY AND TRANSLATION

We studied the impacts of fire-mosaic attributes on the occurrence of Ngarlgumirdi on the Dampier Peninsula. Ngarlgumirdi were more prevalent in areas with higher proportions of habitat that had not burnt for at least 3 years, or had burnt less frequently. Feral cats were less common in these habitats. These results emphasise the importance of reducing fire frequency and protecting long-unburnt vegetation to maintain Ngarlgumirdi habitat, and support a cross-tenure initiative to manage fire more effectively in the region.

**Yawuru:** Gamba nalgumirdi, marlu manyja yagarmurungun miliya, Manyjanyurdany gurdirdi warli yingarrbangngaran gangajunu, warligarra waranygaburu yingarrarlin gangajunu gamba gurlju yirr jaril yagarraman ngarraya. Marlugarriny yagarralangan narlinyurdany jalaluyi janangarru nyamba miliya. Dampiergun juluburu yagarrabaran yirr yagarrabanggan gamba ngurru nalgumirdigarra burugun gamba jarriny ngurru marlu junggu yinganda gurdidiyi wula, buru junggu manyjan wubardujina yinganda yirr marlu manyjan gurdirdi minyaw nyambagun. Nyamba galwaragaja gamba jurrungu yingan yagarramaguran wubardu buruyi junggu yilurran yirr yagarrajalalan buru Marlu jungu yingangany nalgumirdi, barndany yinamalyjan nganinya yagarragurndin jurrungu nyambagun buru.



The translation of this short summary from English into Yawuru language was provided by the Mabu Yawuru Ngan-ga Language Centre. Yawuru language is a Western Nyulnyulan language spoken by people from the Broome region in Western Australia.

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# Where there's smoke, there's cats: long-unburnt habitat is crucial to mitigating the impacts of cats on the Ngarlgumirdi, greater bilby (*Macrotis lagotis*)

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## ABSTRACT

**Context.** The decline of the greater bilby (*Macrotis lagotis*), or Ngarlgumirdi (Yawuru), like other critical-weight range Australian mammals, is believed to be primarily due to the synergetic impacts of predation by feral cats and foxes, habitat disturbance caused by large introduced herbivores, and increases in the frequency and intensity of wildfires. Although it has been demonstrated that low-intensity prescribed burning mosaics in some habitats have the potential to benefit mammals, including Ngarlgumirdi, by creating habitat with sufficient vegetation cover, the contributions of specific fire-mosaic attributes to Ngarlgumirdi persistence remain unclear. **Aims.** To elucidate the impacts of fire-mosaic attributes on the occupancy of Ngarlgumirdi on the Dampier Peninsula. **Methods.** We used 2-ha sign-plot data collected by four Indigenous Ranger groups, in combination with 20 years of satellite-derived fire-history information to investigate the multiscale impacts of fire attributes on Ngarlgumirdi and feral cats (*Felis catus*) on the Dampier Peninsula in the West Kimberley region, a large, unfenced landscape in the most fire-prone section of the Ngarlgumirdi's current range. **Key results.** We found that Ngarlgumirdi was more common in areas that had a higher proportion of habitat that had not burnt for at least 3 years, whereas feral cats were less prevalent in these areas. Similarly, Ngarlgumirdi was less likely to occur in landscapes affected by frequent fires, whereas cats were more common there. **Conclusions.** Our findings have highlighted the importance of decreasing fire frequency and increasing the extent of long-unburnt habitats (>3 years) for preserving Ngarlgumirdi on the Dampier Peninsula and mitigating ecological damage inflicted by feral cats. Findings were consistent across spatial scales (1-, 3-, 5- and 10-km radius from each monitoring site). **Implications.** These results have demonstrated the potential of fire management to increase native species resilience in the absence of direct feral cat control methods. Further, they support a recent cross-tenure initiative led by Traditional Owners to implement fire management that aims to reduce large, frequent high-severity wildfires and increase areas of long-unburnt vegetation on the Dampier Peninsula.

**Keywords:** applied ecology, biodiversity, conservation ecology, conservation management, ecological function, ecological systems, ecology, ecosystem management, natural resource management.

## Introduction

Since European colonisation, Australia's diverse mammal fauna has been affected by species loss and high rates of population decline (Woinarski *et al.* 2015), particularly those species in the small to medium size range (Johnson and Isaac 2009). Although most known extinctions took place in southern and arid regions of Australia during the early years of colonisation (Woinarski *et al.* 2015), recent mammal declines in northern

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Australia's tropical savannas have occurred in areas that were largely unaffected until much later (McKenzie 1981; Burbidge and McKenzie 1989; Woinarski *et al.* 2011; Ziembicki *et al.* 2013), and similarly appear most prevalent among species in the small to medium size range (35–5500 g) (Murphy and Davies 2014).

A broad suite of factors has been attributed to mammal declines in southern Australia, including predation by introduced foxes and feral cats (Abbott *et al.* 2014), changing fire regimes, and the spread of large-scale agriculture and introduced herbivores (Woinarski *et al.* 2015). However, declines in northern Australia remain less clearly understood (Stobo-Wilson *et al.* 2020). Although evidence suggests that feral cats play a role, the decline of northern Australian mammals in the late 20th century is likely to be attributable to a combination of factors (Woinarski *et al.* 2011; Davies *et al.* 2020; Radford *et al.* 2021). One such factor is the frequent, high-intensity fires that have become increasingly common in northern Australia since the cessation of traditional Indigenous burning practices (Santos *et al.* 2022). Although the effects of these fires on mortality may be modest (Jolly *et al.* 2022), they have been shown to reduce the availability of resources, particularly for species that rely on vegetation cover. Moreover, the interaction between predators and fire further complicates the survival of these species, because altered habitats from fire events can make it easier for predators such as feral cats to hunt (McGregor *et al.* 2015), thereby exacerbating the impact on native fauna (Geary *et al.* 2020; Doherty *et al.* 2022).

Although there is evidence that supports the concept of predation as a primary driver of northern Australian mammal declines, with changed disturbance regimes exacerbating impacts (Griffiths *et al.* 2015; Lawes *et al.* 2015; Leahy *et al.* 2016; Radford *et al.* 2021), there is still much to be understood from a management perspective (Griffiths and Brook 2014). For example, although it has been demonstrated that low-intensity prescribed burning mosaics in some habitats have the potential to benefit mammals by reducing wildfires and creating habitat with sufficient vegetation cover (Davies *et al.* 2018; Radford *et al.* 2020), the contributions of specific fire-mosaic attributes to species persistence remain unclear. Further, whereas the scale at which these attributes are most important has been examined for some species (e.g. Legge *et al.* 2019), for the majority of species this detail remains poorly understood. Improving our understanding of these factors is crucial from a conservation management perspective to design effective interventions for threatened species across Australia's north.

The greater bilby (*Macrotis lagotis*) is a medium-sized burrowing marsupial that was once widespread in Australia's arid and semi-arid regions. The species is now restricted to a northern subset of its former range (DCCEEW 2023) and is listed as vulnerable by the IUCN (Burbidge and Woinarski 2016). The decline of the bilby, like other critical weight-range Australian mammals (Woinarski *et al.* 2015), is

believed to be primarily due to impacts of predation (Southgate 1990), which are thought to be exacerbated by grazing from introduced herbivores, and frequency and intensity of wildfire (Abbott 2001; Doherty *et al.* 2015a; DCCEEW 2023), both of which can cause changes to habitat and resource availability through modification of vegetation structure, composition and cover (Bowman *et al.* 2020). Further understanding of the interactive effects of fire and predation is a research priority for the bilby (Cramer *et al.* 2016), particularly in the most fire-prone areas of its range where the synergetic impacts from these threats are likely to be greatest. Previous research investigating these threats is mostly limited to arid areas of the species range (Southgate 1990; Southgate *et al.* 2007), although see Dawson (2017). Results suggest that whereas bilby occurrence tends to be negatively correlated with predators such as the fox, the effect of fire on its distribution appears relatively weak. However, there does appear to be a preference for habitat located in close proximity to burnt areas in arid systems (Southgate *et al.* 2007), which is likely to be due to the high availability of fire-promoted food plants (Southgate and Carthew 2006). Whether bilbies respond similarly in habitats that burn more frequently, or how fire influences their vulnerability to predators in these environments, remain unclear.

The Dampier Peninsula in the Kimberley region of north-western Western Australia represents the most tropical extent of the current range of the bilbies, receiving an average of 650–850 mm of rain per year (BOM 2022), and is extremely prone to fire (NAFI 2022). Although the response of bilbies to fire has previously been investigated on part of the Dampier Peninsula (Dawson 2017), a more broad-scale approach is required to assist in developing fire management guidelines for bilbies in this area, which has been identified as a priority action in the most recent greater bilby recovery plan (DCCEEW 2023). Evidence from nearby caves suggests that Aboriginal peoples have been living in this region for at least 46,000 years (Balme *et al.* 2019). Like in other parts of Australia prior to European colonisation (Enright and Thomas 2008), fire-management practices implemented by Aboriginal peoples are likely to have played a significant role in shaping the ecosystems of the Kimberley (Vigilante 2001). This includes creating fine-scale habitat mosaics and limiting the extent of large-scale wildfires, both of which can be favourable for native mammals (Bowman 1998). Although contemporary burning patterns in the Kimberley are still influenced by people (Vigilante *et al.* 2004), the large-scale migration of Aboriginal pastoral workers and their families into towns and communities following the introduction of equal pay in 1968 (Jebb 2002) has largely removed traditional burning practices from the landscape. Concurrently, the demand for labour as part of the Dampier Peninsula's pearling industry contributed to social disruption within Aboriginal communities, and thus also the pre-existing fire regime, because people were often forcibly removed from their lands to work in pearling or were displaced by the

industry infrastructure and activities (Nilsson 2017). These developments, alongside other social factors, have contributed to shaping current fire regimes in large parts of the Kimberley, including the Dampier Peninsula, which became largely characterised by extensive mid-to-late season wildfires, often reoccurring on a 1–3-year cycle (Russell-Smith *et al.* 2003a).

In addition to human life and property, large-scale wildfire on the Dampier Peninsula threatens species and communities that are of high cultural and ecological value (Wysong *et al.* 2021). For example, an ecological community endemic to the Dampier Peninsula, the monsoon vine thicket, is now listed as Endangered nationally, in part owing to increased fire frequency in areas where it occurs (DCCEEW 2013). For thousands of years, the monsoon vine thickets have provided Aboriginal peoples with food, tools, medicines, shelters, and meeting places, while also providing important habitat for native fauna (Lindsay *et al.* 2022). Like the monsoon vine thickets, bilby, hereafter referred to as *Ngarlgumirdi*, the name used by Yawuru people from the Broome region, is an ecologically important species that has likely been adversely affected by changing fire regimes on the Dampier Peninsula. *Ngarlgumirdi* holds significant cultural importance to the Traditional Owners of the Dampier Peninsula, as well as other sections of its current and former range, and frequently features in the ancestral narratives often referred to as The Dreaming (Skroblin *et al.* 2022; DCCEEW 2023). Protecting *Ngarlgumirdi*, along with other important species and communities from the damaging impacts of wildfire is a priority for Traditional Owners on the Dampier Peninsula. Achieving this aim requires a coordinated approach, such as that implemented by the Dampier Peninsula Fire Working Group, a collaboration led by Indigenous Ranger groups, pastoralists, fire managers and other stakeholders, that aims to improve fire regimes on the Dampier Peninsula (Wysong *et al.* 2021). To help focus these efforts so as to improve *Ngarlgumirdi* persistence, we investigated the multiscale impacts of different fire attributes on *Ngarlgumirdi* across the Dampier Peninsula, and also examined how these fire attributes influence the occurrence of feral cats, an important predator of the species (Moseby *et al.* 2011). The implications of the patterns observed are discussed in relation to enhancing *Ngarlgumirdi* conservation through improved fire management within the study area.

## Methods

### Study area

The study area was located on the Dampier Peninsula within the western Kimberley region of north-western Australia (Fig. 1). Covering ~18,000 km<sup>2</sup>, the area comprises Indigenous Protected Areas, pastoral leases, unallocated Crown Land as well as a small nature reserve (Coulomb Point). This area represents the most north-western section of the *Ngarlgumirdi*'s

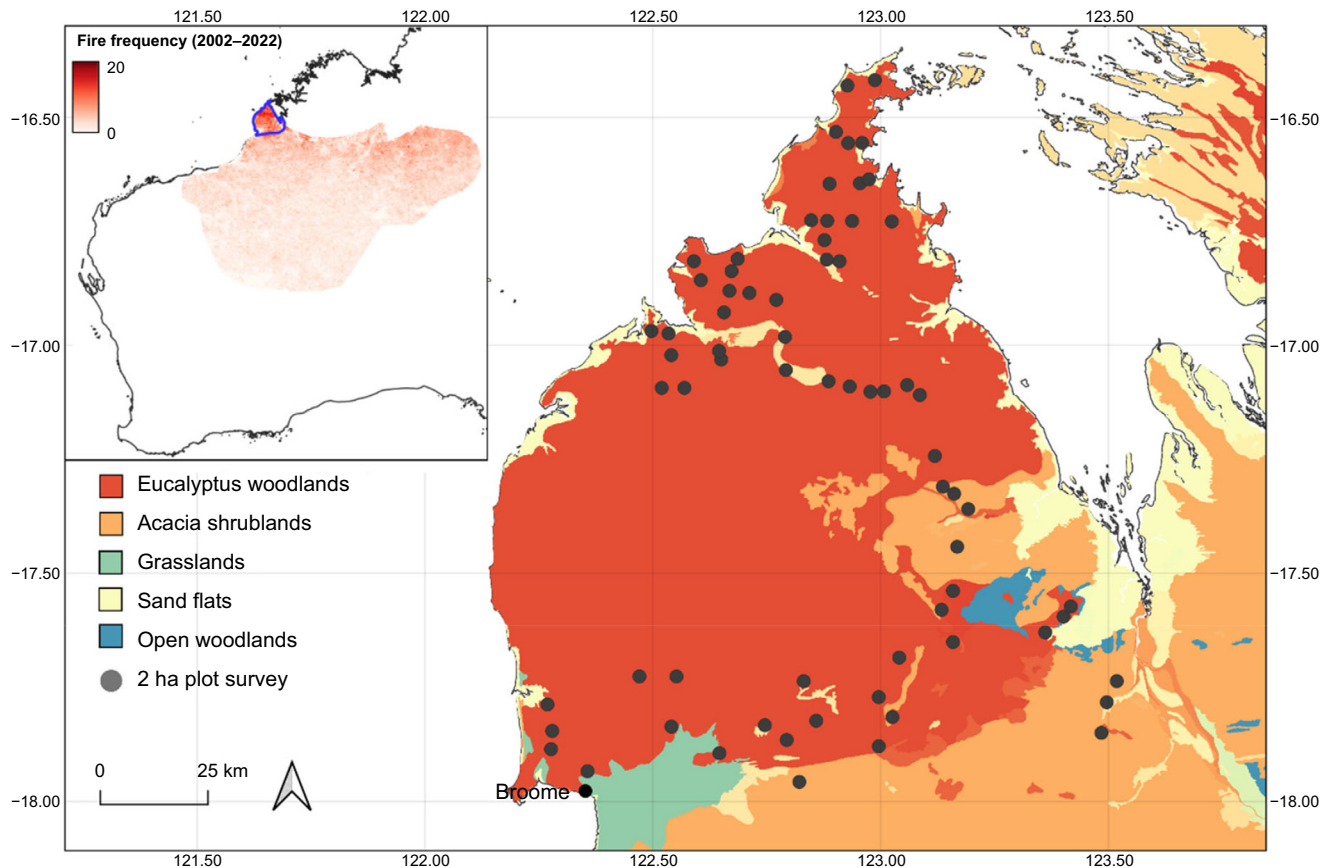
contemporary and historic range (Southgate 1990), and also the section of their contemporary range that receives the most annual rainfall (BOM 2022) and burns the most frequently (NAFI 2022). The majority of land within the study region is subject to a determined or registered Native Title Claims (National Native Title Tribunal 2023). The area experiences a tropical monsoonal climate, with the majority of rainfall falling between December and March. Annual rainfall totals across the peninsula typically range from ~650 mm in the south to ~850 mm in the north (BOM 2022).

Vegetation on the Dampier Peninsula is largely dominated by eucalypt woodlands (*Eucalyptus tectifica*, *Corymbia polycarpa*, *Corymbia grandifolia*) and acacia shrublands (*Acacia tumida*, *A. eriopoda*) over a sparse understorey comprising herbs, and mixed annual and perennial grasses (*Sorghum stipoides*, *Chrysopogon pallidus*, *Senna notabilis*, *Ptilotus corymbosus*) (Kenneally *et al.* 1996; Dziminski and Bettink 2017) (Fig. 2). Within these communities, *Ngarlgumirdi* tends to be associated with species that harbour root-dwelling larvae (*A. colei*, *A. eriopoda*, *A. tumida*, *Grevillea refracta*, *Dodonaea hispidula*, *S. notabilis*), which are an important component of its diet (Dziminski and Bettink 2017; Southgate *et al.* 2019). These habitat types provide a mix of more open areas for mobility and sufficient vegetation cover for protection from predators.

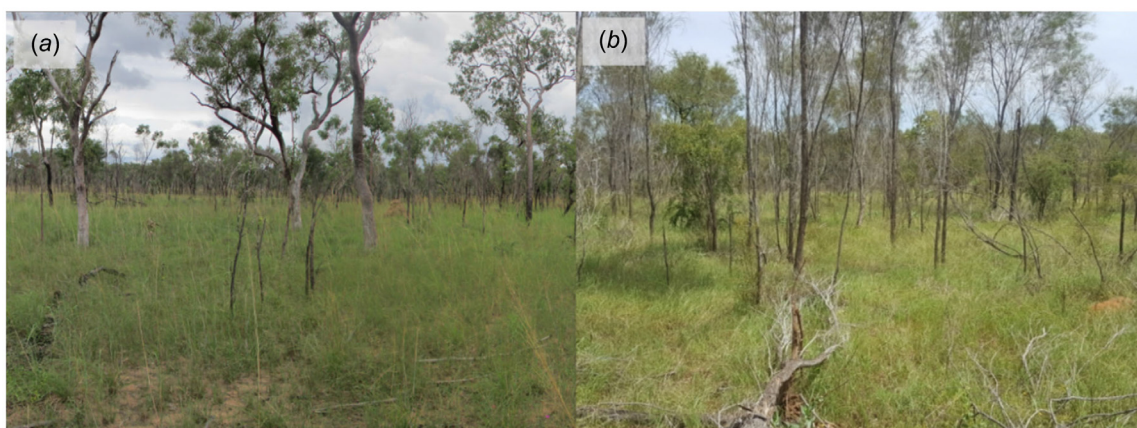
### Fire management on the Dampier Peninsula

Fire management on the Dampier Peninsula is primarily the responsibility of landowners, with state-owned land managed by designated authorities such as the Department of Biodiversity, Conservation and Attractions (DBCA; DPLH 2022). Natural events such as lightning, as well as human factors, including campfires, discarded cigarettes, and deliberate arson, are the main contributors to wildfire ignition on the Dampier Peninsula. The intensity and spread of these fires are influenced by available fuel and moisture content; however, under certain conditions, fires can burn over 6500 km<sup>2</sup> in the space of a single month (NAFI 2022). As the region navigates the challenges of managing fires of this scale, there is an ongoing effort to reintegrate traditional burning practices into broad-scale fire management.

The Dampier Peninsula Fire Working Group (DPFWG) was established in 2016 as a collaborative initiative that brings together Traditional Owners, Indigenous Ranger groups, government agencies, conservation and non-profit organisations, as well as the pastoral and natural resources industries (Wysong *et al.* 2021). Emphasising Aboriginal-led management as a core principle, the group is dedicated to enhancing fire management on the Peninsula through coordinated training, skills-sharing, communication, and prescribed burning efforts. A focus on Aboriginal leadership ensures that traditional knowledge and practices play a central role in shaping fire-management strategies, reinforcing the importance of culturally informed conservation efforts.



**Fig. 1.** Location of 2-ha sign plots located on the Dampier Peninsula in north-western Australia. Inset shows fire frequency across the Ngarlgumirdi's (*Macrotis lagotis*) contemporary range (excluding the isolated Queensland population), with the study area outlined in blue.



**Fig. 2.** Dominant vegetation types on the Dampier Peninsula in north-western Australia. (a) *Eucalyptus* woodland, comprising Dampier bloodwood (*Corymbia* sp.) over sparse to dominant blade grass (*Chrysopogon pallidus*) and *Jacquemontia* sp. (b) *Acacia* shrubland, comprising mixed acacia (*Acacia tumida*, *A. coleii*) over tussock grass.

### Dampier Peninsula bilby-offset project

In 2016, Main Roads Western Australia provided offset funding (associated with the Cape Leveque Road upgrade) to the Western Australian Department of Biodiversity

Conservation and Attractions, to undertake a 3-year project to survey, monitor and commence adaptive management of threats to Ngarlgumirdi populations across the Dampier Peninsula, including fire (Dzimirski and van Leeuwen 2019). Partners on this project included Nyul Nyul, Bardi Jawi

Oorany, Nyikina Mangala Indigenous Rangers, and Yawuru Country Managers.

Data used in this study were collected during the first component of this project, which, in addition to measuring the influence of fire-mosaic attributes on Ngarlgumirdi occurrence, aimed to map Ngarlgumirdi occurrence across the Dampier Peninsula. Other project objectives included implementing fine-scale fire management at a select number of sites where Ngarlgumirdi was confirmed to be present, in conjunction with an annual abundance-monitoring program using a scat-genotyping approach (Dziminski and van Leeuwen 2019).

### Presence data

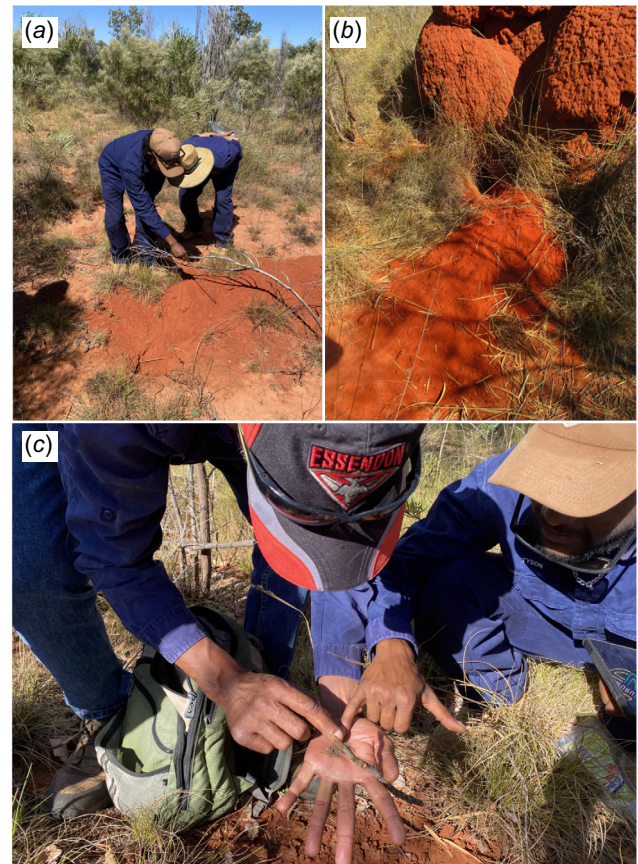
Ngarlgumirdi and feral cat-presence data were collected at 69 sites across the study area, between April and October 2019. The average distance between a site and its nearest neighbouring sites was 5.7 km (minimum = 2.5 km; Fig. 1). Although Ngarlgumirdi is known to move distances of up to 5 km between burrows (DCCEEW 2023), the majority of sites were deemed to be suitably independent from one another. Collaborative planning sessions for sign-plot locations were conducted with Nyul Nyul, Bardi Jawi, Nyikina Mangala Rangers and Yawuru Country Managers on the basis of their local knowledge of suitable habitats. The location of sites was stratified according to fire frequency by using data collected from the North Australia Fire Information Service (NAFI 2022).

Species presence at sites was verified using the 2-ha sign-plot approach, which involved trained sign observers searching a 2-ha area (100 m × 200 m) for secondary signs, including tracks, diggings and scats, for 25 min (Moseby *et al.* 2009) per visit. The 2-ha sign-plot approach is currently one of the most widely used methods for detecting Ngarlgumirdi (Bradley *et al.* 2015; Southgate *et al.* 2019; Dziminski *et al.* 2021a, 2021b), especially by Indigenous Ranger groups (Paltridge 2016). In addition to Ngarlgumirdi, this survey method is also effective at detecting a range of other vertebrates, including introduced predators such as feral cats (Moseby *et al.* 2009).

Sites were surveyed at least twice by Nyul Nyul, Bardi Jawi, Nyikina Mangala Rangers and Yawuru Country Managers between March and October 2019, with most sites being surveyed four times ( $n$  total visits = 259; Fig. 3). Repeat visits were used to track changes in site occupancy at different post-fire successional stages. The average interval between surveys was 65 days. Only fresh sign was used to record presence.

### Environmental data

Fire data used in this study comprised Moderate Resolution Imaging Spectroradiometer (MODIS; 250-m resolution) vector data available from the North Australia Fire Information service (<http://firenorth.org.au>). The status of data pixels (burnt or unburnt) was measured on a monthly basis from



**Fig. 3.** Yawuru Country Managers conducting 2-ha plot surveys to record presence of Ngarlgumirdi and feral cats. (a) Country Managers investigating a fresh Ngarlgumirdi burrow (b) a fresh Ngarlgumirdi burrow (c) Country Managers investigating Ngarlgumirdi scat material.

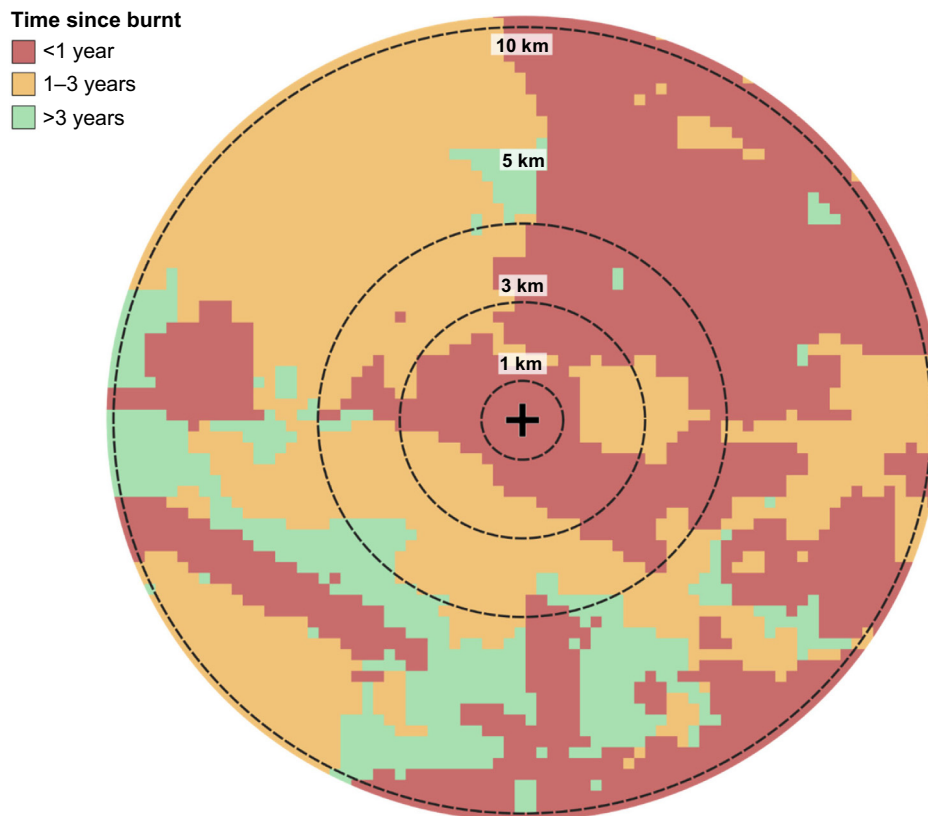
the Year 2000 up until the date a 2-ha plot was completed. Four fire-history attributes were recorded for each site, and each visit, by using MODIS data. Fire attributes were pyrodiversity, fire frequency, as well as proportion of site recently burnt (<1 year post fire) and long unburnt (>3 years post fire) (Table 1). Long unburnt habitat was defined as an area that was last burnt more than 3 years prior, in accordance with the study by Wysong *et al.* (2021) conducted in the same study area.

Research has shown that fire attributes can have varying impacts on species depending on the scale at which they are measured (Nimmo *et al.* 2019; Wan *et al.* 2020). To account for this, we measured fire attributes at multiple scales for each plot location (Fig. 4). We did this by creating buffers of different sizes at each plot location, and then clipping fire data to those buffers, following Radford *et al.* (2021). Buffer sizes were 1 km ( $A = 3.14 \text{ km}^2$ ), 3 km ( $28.26 \text{ km}^2$ ), 5 km ( $78.5 \text{ km}^2$ ) and 10 km ( $314 \text{ km}^2$ ).

Other environmental factors likely to influence the occurrence of Ngarlgumirdi and feral cats, including dominant vegetation type and recent rainfall (previous 6-month total) were also recorded for each site, at each scale. Vegetation

**Table 1.** Attributes used to assess the influence of fire on the presence of Ngarlgumirdi (*Macrotis lagotis*) and feral cats (*Felis catus*) on the Dampier Peninsula, north-western Australia.

Attribute	Method	Justification
Pyrodiversity	Sum of post-successional vegetation ages within a landscape.	Pyrodiversity refers to the diversity of fire regimes within a landscape. Previous research has suggested that pyrodiversity can be linked to aspects of biodiversity (Martin and Sapsis 1992; Tingley <i>et al.</i> 2016), as well as individual species habitat suitability (Senior <i>et al.</i> 2021), although not always (Jones and Tingley 2022).
Fire frequency	The number of years in which a landscape burnt between the Year 2000 and the time of a 2-ha plot survey.	Fire frequency is an important predictor of fauna biodiversity in northern Australia (Griffiths <i>et al.</i> 2015; Ondei <i>et al.</i> 2020; Andersen 2021), including mammal species (Davies <i>et al.</i> 2018; Einoder <i>et al.</i> 2018).
Proportion recently burnt (<1 year post-fire)	The proportion of a landscape that was burnt up to 1 year before a 2-ha plot survey.	The proportion of recently burnt habitat within a landscape has previously been demonstrated to have a strong influence on mammal presence in northern Australia (Radford <i>et al.</i> 2015). In central Australia, proximity to recently burnt habitat is associated with Ngarlgumirdi occurrence (Southgate <i>et al.</i> 2007)
Proportion longer unburnt (>3 years post-fire)	The proportion of a landscape that was last burnt more than 3 years before a 2-ha plot survey, following Wysong <i>et al.</i> (2021)	Long-unburnt habitat has repeatedly been demonstrated to be important to the persistence of northern Australian mammal species (Davies <i>et al.</i> 2018; Legge <i>et al.</i> 2019; Shaw <i>et al.</i> 2021; Shaw <i>et al.</i> 2021; von Takach <i>et al.</i> 2022)



**Fig. 4.** Spatial scales of buffers used to assess fire attributes on the Dampier Peninsula in northern Australia. In this example, time since burnt is used. The black cross represents the centre of a 2-ha plot location.

data were sourced from the National Vegetation Information System (NDVI 2020) at 100 m × 100 m resolution. The majority of sites (*n* = 65) were dominated by either *Eucalyptus*

woodland or *Acacia* shrublands. The four sites that did not fall into either of these two categories were removed because of inadequate sampling replication. Although substrate is

known to be an important predictor of Ngarlgumirdi occurrence, it was not included in models here, given that almost all sites were located on calcareous and siliceous sands (Rudosols), which are deemed suitable substrate for Ngarlgumirdi occurrence.

## Data analysis

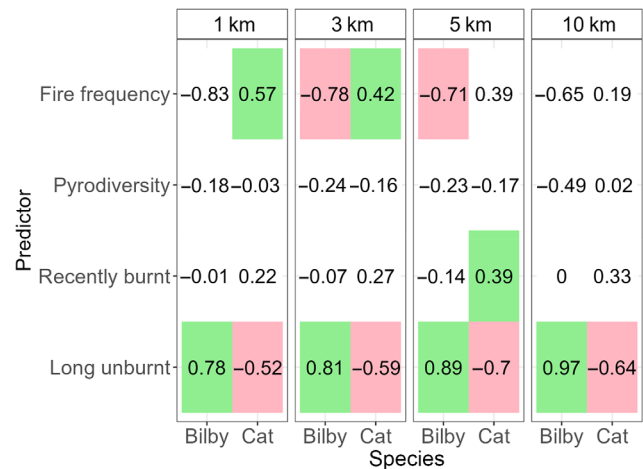
To measure the effect of fire attributes on species' occurrences, we fit binomial generalised linear mixed-effects models by using the lme4 package (Bates *et al.* 2015) in R ver. 4.1.2 (R Core Team 2021). A global model was fit for each fire attribute (pyrodiversity, fire frequency, proportion recently burnt, and proportion longer unburnt), at each scale (1 km, 3 km, 5 km, 10 km), for each species (Ngarlgumirdi, feral cat). To avoid collinearity issues, separate models were fitted for each fire attribute. This resulted in a total of 16 models per species (four fire attributes  $\times$  four scales). The presence or absence of species at each site on each visit was set as the response variable for all models.

In addition to fire attributes, each global model included vegetation type and recent rainfall (previous 6 months) as fixed effects. The site ID was included in the models as a random factor to account for sampling replication within sites. Fixed effects were deemed to have a strong effect on species occurrence when estimate confidence intervals did not overlap zero (Nakagawa and Cuthill 2007).

## Results

Ngarlgumirdi was recorded at 18.8% of the sites. Ngarlgumirdi presence was influenced by the proportion of long-unburnt habitat, with the largest effect being observed at the largest scale (10 km) (Fig. 5). Here, the likelihood of Ngarlgumirdi presence increased from absent (0%) when there was no  $>3$  years unburnt habitat within a 10-km radius of the site, to 24.2% when the entire area within a 10-km radius site was  $>3$  years unburnt (Figs 5, 6). Fire frequency also influenced Ngarlgumirdi presence at the 3-km and 5-km scales. At the 3-km scale, presence decreased from 34.8% at sites that had been burnt seven times in the previous 20 years to 0% at sites that had been burnt 20 times in the same period (Fig. 6). Predictions of Ngarlgumirdi occurrence were associated with wide confidence intervals, which were likely to be due to the limited sample size.

Feral cats were recorded at 59.4% of the sites. Feral cat presence was also related to the proportion of long-unburnt habitat, but the effect was inversed when compared with Ngarlgumirdi (Fig. 5). The likelihood of feral cat presence decreased by 30% from sites with no surrounding long-unburnt habitat to sites surrounded by 100% long-unburnt habitat. This effect was consistent across spatial scales (Fig. 6). The likelihood of feral cat presence increased with an increasing fire frequency at the 3-km and 5-km scales, as



**Fig. 5.** Model estimates from generalised linear mixed-effects models testing the influence of fire attributes on the presence of Ngarlgumirdi and feral cats on the Dampier Peninsula in north-western Australia. Coloured cells show estimates where the effect was significant ( $P < 0.05$ ). Red cells indicate a negative effect, and green cells indicate a positive effect.

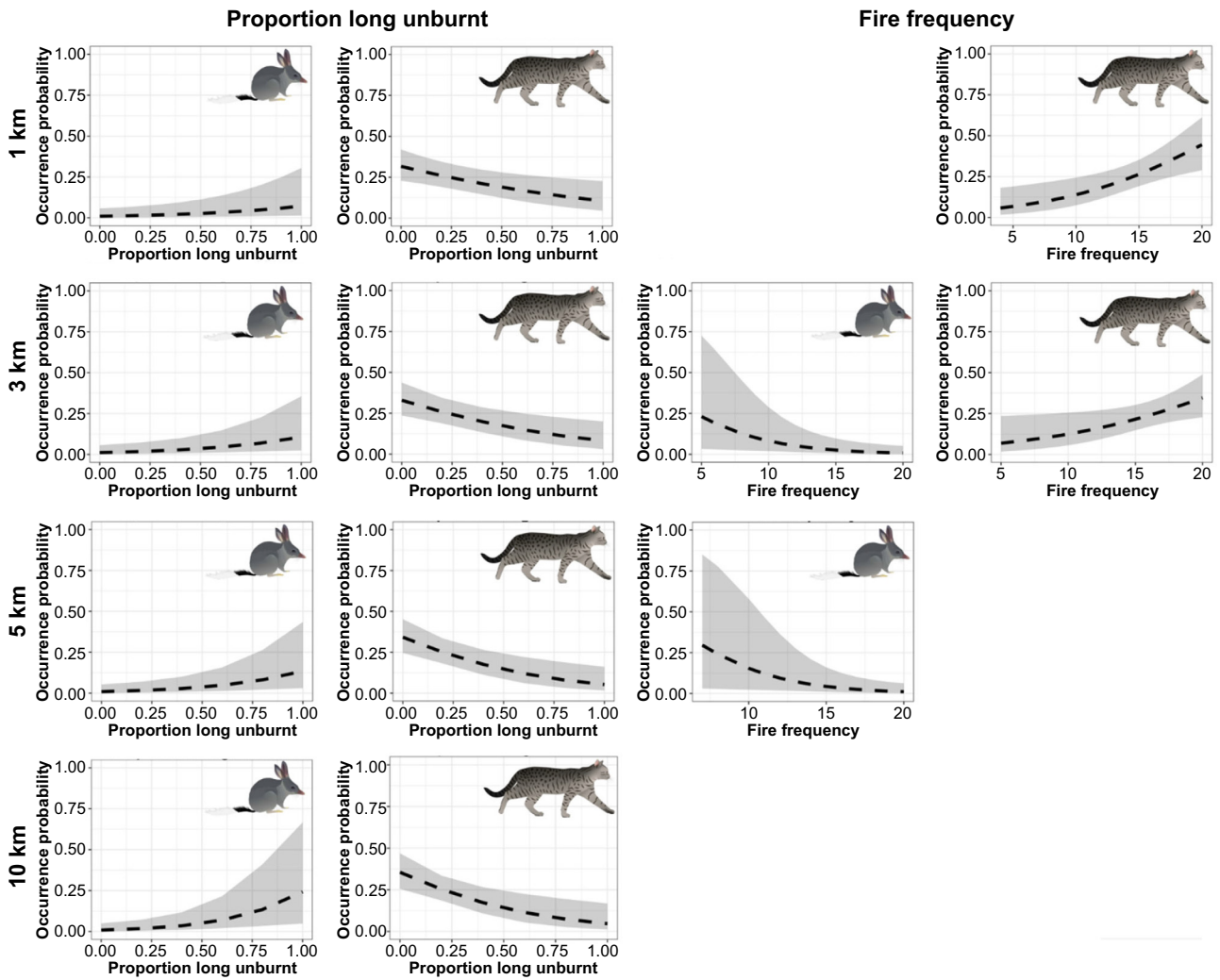
well as the proportion of recently burnt habitat at the 5-km scale. Pyrodiversity, annual rainfall and dominant vegetation type had no significant influence on the presence of Ngarlgumirdi or feral cats at any scale (Supplementary Tables S1, S2, S3, S4).

## Discussion

Our findings indicated that fire frequency and the extent of long-unburnt habitat ( $>3$  years) are important factors in predicting the presence of both Ngarlgumirdi and feral cats across multiple spatial scales in the highly fire-prone landscape of the Dampier Peninsula. Ngarlgumirdi was more frequently detected in areas with a high proportion of habitat that had not been burnt for at least 3 years, whereas feral cat detections were lower here. Similarly, frequent fires tended to be a deterrent for Ngarlgumirdi, but not for feral cats. These results support findings from global studies that suggest that trends of increasing fire frequency and spatial extent of fires have contributed to declines observed across multiple taxa, presumably owing to an increase in predation and decrease in resource availability (Engstrom 2010; Kelly *et al.* 2020). These results provide important context for fire practitioners seeking to implement fire regimes that promote habitat suitable for the conservation of Ngarlgumirdi within fire-prone areas of their range, particularly on a landscape scale outside of invasive-predator-free enclosures.

### How does fire influence the distribution of Ngarlgumirdi on the Dampier Peninsula?

Previous studies that examined the interaction between Ngarlgumirdi and fire have mostly focused on arid environments,



**Fig. 6.** Model predictions from generalised linear mixed-effects models testing the influence of fire attributes on the presence of Ngarlgumirdi and feral cats on the Dampier Peninsula in north-western Australia. Grey shading indicates 95% confidence intervals. Each row shows predictions from models using data collected at varying distances from 2-ha plots (1 km, 3 km, 5 km, 10 km).

such as in the Tanami Desert. In these drier locations, there is evidence to suggest that Ngarlgumirdi occurs more frequently in close proximity to recently burnt habitat (Southgate *et al.* 2007), likely owing to the increased availability of post-fire ephemeral grasses (Southgate and Carthew 2007), which can make up a substantial proportion of their diet in arid areas (Southgate and Carthew 2006). Whereas one previous study has investigated the response of Ngarlgumirdi to fire on the Dampier Peninsula, finding limited evidence of a response (Dawson 2017), our research expands on this methodology by using a landscape approach across multiple scales and incorporating a larger study area.

In contrast to arid environments where Ngarlgumirdi is known to prefer recently burnt habitat, we found that Ngarlgumirdi on the Dampier Peninsula was more likely to occur in areas that had not been burnt for at least 3 years (Southgate and Carthew 2007). The observed disparity in

habitat preference between arid ecosystems and the current study area may be attributed to differences in the post-fire composition and structure of the vegetation in the higher-rainfall Dampier woodlands from those in arid grasslands. For example, in arid landscapes, post-fire spinifex grasslands are usually characterised by low vegetation cover that lasts for 1–3 years, thereby creating an open environment where Ngarlgumirdi can forage for fire-promoted plants such as *Yakirra*. In contrast, in more tropical climates such as the Dampier Peninsula, burnt landscapes are often rapidly colonised by fast-growing annual grasses such as *Sorghum stipoides* (Radford *et al.* 2015; Radford and Fairman 2015). This is likely to be especially true for fires that occur in the late-dry season, given the wettest part of the year generally follows soon after, promoting rapid vegetation growth. By dominating the understorey, these annual grasses are likely to reduce the availability of important perennials such as

*Yakirra* spp. and impede the movement of Ngarlgumirdi while foraging. This result highlights the value of undertaking research across the full range of a wide-ranging habitat generalist such as Ngarlgumirdi to better understand ecological associations that may differ across their range.

We found that Ngarlgumirdi favoured habitat that had been less frequently burnt. This result is supported by previous research in northern Australia, where mammal declines have often been linked to high fire frequencies (Woinarski *et al.* 2010; von Takach *et al.* 2020; Einoder *et al.* 2023). High fire frequencies alter vegetation communities by promoting species with high fire tolerance, and displacing species that are fire sensitive (Russell-Smith *et al.* 2003b; Rossiter *et al.* 2003; Miller *et al.* 2010). In addition to killing invertebrate prey and outcompeting native grasses and herbs, which may be important food sources for Ngarlgumirdi (Gibson 2001), these changes can substantially increase the flammability of landscapes, further increasing fire frequency, intensity and scale (Russell-Smith *et al.* 2003b). Similar effects have been observed within the study area (Wysong *et al.* 2021), with major increases in highly flammable annual *Sorghum*, and this is thought to be at least partly responsible for the disappearance of a long-term local Ngarlgumirdi population. In this example, an intense late dry-season fire replaced stands of *Acacia tumida*, a plant species important for harbouring cossid larvae which are preyed on by Ngarlgumirdi, with annual sorghum grasslands. These changes in the vegetation led to a repeat late dry-season fire event 2 years following the fire, after which Ngarlgumirdi was no longer present at the site (B. Greatwich, unpubl. data).

### How does fire influence the distribution of feral cats on the Dampier Peninsula?

In contrast to Ngarlgumirdi, we found that the likelihood of feral-cat presence increased as the extent of long-unburnt habitat decreased, and fire frequency increased. Although the literature suggests that the response of feral cats to fire is variable and dependent on habitat type (Doherty *et al.* 2015b, 2022), there is evidence that cats do target areas frequently affected by disturbance in tropical savannas (McGregor *et al.* 2014; Davies *et al.* 2020). The most widely accepted explanation for this behaviour is related to prey access, because feral cats can locate and pursue prey more easily in structurally simple habitat (Geary *et al.* 2020). For example, previous studies conducted in the savannas of the Kimberley and Cape York Peninsula regions by McGregor *et al.* (2014, 2015) demonstrated that feral cats exhibit improved hunting efficiency in grassland and recently burnt habitats. Similarly, Trewella *et al.* (2023) found that habitat use by feral cats was most frequent in areas with high fire frequencies and low tree basal area. It is plausible, therefore, that mature *Acacia* shrubland and eucalypt woodland (>3 years post fire) limit the hunting efficiency of feral cats by providing complex vegetation cover for Ngarlgumirdi.

In addition to the immediate reduction in vegetation cover caused by fire, long-term reductions in shrubland/woodland structural complexity caused by repeated fires at short intervals are also likely to benefit feral cats, likely to the detriment of Ngarlgumirdi (Davies *et al.* 2020; Stobo-Wilson *et al.* 2020). It is important to note that the behaviour of feral cats in response to fire is likely to vary in more arid sections of the Ngarlgumirdi's range. For instance, in contrast to our findings, a recent study in arid Australia observed that feral cats not only sought out habitats indicating the presence of native prey, including Ngarlgumirdi, through signs like foraging digs, burrows, and scats, but they also frequently occupied areas with dense vegetation cover (Moseby and McGregor 2022). These insights underscore the need for adaptive management strategies that consider the variable responses of feral cats across different habitats.

### Management implications

Our findings have highlighted the importance of decreasing the frequency of large-scale wildfire and increasing the amount of long-unburnt habitat (>3 years) for the preservation of Ngarlgumirdi and the mitigation of ecological damage inflicted by feral cats on the Dampier Peninsula. For example, on the basis of model predictions at the 3-km scale (a logistically feasible management unit), increasing the proportion of long-unburnt habitat in the landscape from 20% to 60% could almost triple the likelihood of Ngarlgumirdi occurrence, and almost halving the likelihood of feral-cat occurrence. Similarly, reducing fire frequency from once every 2 years to once every ~4 years more than triples the likelihood of Ngarlgumirdi occurrence, and halves the likelihood of feral-cat occurrence. These targets align directly with objectives established by the Dampier Peninsula Fire Working Group (DPFWG) (Wysong *et al.* 2021). A recent review of the project performance in relation to these objectives demonstrated that fire-management efforts in the region increased the extent of vegetation long unburnt from 18% in 2015 to 65% in 2020 (Wysong *et al.* 2021). In addition, the proportion of habitat burnt three or more times was halved over the same period. Our study supports the ongoing burning planning and practices being implemented by DPFWG that aim to increase the extent of long-unburnt vegetation on the Dampier Peninsula and reduce fire frequency.

### Future research

Although our study has provided important insights into the roles of fire frequency and the extent of long-unburnt habitat on the distribution of Ngarlgumirdi and feral cats in the Dampier Peninsula, several avenues for future research are evident. One is investigating how changes in understorey and overstorey vegetation complexity influence the likelihood of Ngarlgumirdi occurrence. Although it is likely that these metrics are correlated with fire metrics (Fisher *et al.* 2003; Lynch *et al.* 2018; Rainsford *et al.* 2020), a more detailed

understanding of how Ngarlgumirdi responds to vegetation structure *per se* could provide important insights into how habitat suitability can be better managed, particularly for populations located within pastoral leases where grazing pressure is a threat (Dziminski *et al.* 2021b). Incorporating burn timing and severity as additional predictors is also likely to offer a more nuanced understanding of how Ngarlgumirdi responds to fire in this region (Southgate and Carthew 2007). Both factors are likely to be strong determinants in the response of vegetation in terms of structure and composition (Russell-Smith and Edwards 2006). Moreover, since both fire severity and timing are key metrics used to gauge the success of current fire management in the region (Wysong *et al.* 2021), quantifying the response of Ngarlgumirdi to these variables could enhance our ability to tailor burn plans to improve Ngarlgumirdi conservation.

It is important to note that the 2-ha sign-plot method used in this study was initially developed for arid environments, where animal sign, particularly tracks, are more easily detected because of the predominance of open sandy areas. Although Ngarlgumirdi diggings and burrows are typically visible regardless of substrate, high vegetation cover within the study area may have reduced Ngarlgumirdi and feral-cat detectability at some sites. To overcome this issue, we suggest future studies couple plot surveys with camera-traps, so that species presence can be better verified.

Finally, improving our understanding of how Ngarlgumirdi diets vary with fire history, similar to what has already been undertaken in other parts of their range (Gibson 2001; Southgate and Carthew 2006), should also be a focus of future research. Integrating this knowledge into burn regimes could enable fire practitioners to actively manage Ngarlgumirdi food resources and expand the extent of suitable habitat available.

## Supplementary material

Supplementary material is available [online](#).

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**Data availability.** Data will be made available on FigShare following publication.

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