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Research priorities for the ghost bat (*Macroderma gigas*) in the Pilbara region of Western Australia

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ABSTRACT

The ghost bat (*Macroderma gigas*) is Australia's largest echolocating bat. It is restricted to several disjunct populations in the north of the continent, including a population in the Pilbara region of Western Australia. In 2016 the ghost bat was listed as Vulnerable under Australian federal legislation, owing to declining numbers across many regional populations. The most severe threat to ghost bats in the Pilbara region is the destruction and disturbance of habitat due to mining operations, but disturbance to their roosts from other infrastructure developments and changes to and loss of foraging habitat also pose significant threats. A set of research priorities for ghost bats in the Pilbara was developed during a workshop attended by mining industry representatives, environmental consultants, scientists and government regulators. Five research priorities were identified: (1) identify and characterise critical diurnal roosts and foraging habitat; (2) improve knowledge of the distribution, movement and dispersal patterns of ghost bats in the region; (3) improve knowledge of population size, persistence and long-term trends; (4) better understand the cumulative, direct and indirect impacts of mining and other development activities; and (5) better understand the threats posed by fence entanglements, cane toads and feral cats.

Keywords: cane toads, colony, conservation, dispersal, distribution, diurnal roost, fence, feral cats, foraging, habitat, mining, population, threats.

Introduction

The ghost bat (*Macroderma gigas*) is the largest Australian echolocating bat and one of the most distinctive, with its pale fur, simple nose-leaf, long ears and large eyes (Richards *et al.* 2008). Fossil and guano records show that ghost bats were once distributed widely across Australia but they have disappeared from southern and central regions (Churchill and Helman 1990; Baynes and Baird 1992). Their contraction northwards to more tropical biomes has been attributed to the drying of the climate in southern Australia before the last glacial maximum (Molnar *et al.* 1984; Churchill and Helman 1990; Thomson 2012). The more recent disappearance of ghost bats from central Australia by the mid-twentieth century is linked to European colonisation, and the consequent decline of numerous other mammal species. The loss of continuous food resources in a climate near the limit of the ghost bat's physiological tolerances may have triggered its extirpation (Burbidge *et al.* 1988; Churchill and Helman 1990).

Ghost bats are currently distributed in several disjunct populations across northern Australia: from Rockhampton to Cape York in north Queensland; the Gulf Coastal and Mount Isa Inlier bioregions in the southern Gulf of Carpentaria; the Top End of the Northern Territory; and the Kimberley and Pilbara regions of Western Australia (Woinarski *et al.* 2014; Armstrong *et al.* 2019). This disjunct distribution reflects the limited availability of suitable cave roosts in the intervening monsoonal and arid areas of northern Australia (Worthington Wilmer *et al.* 1999).

The ghost bat was listed as Vulnerable under the Australian Government's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) in May 2016, owing to declines of >30% in numbers across its range (Threatened Species Scientific Committee 2016*a*), and is listed as Vulnerable by the IUCN. Additionally, the ghost bat is listed as Endangered in Queensland, Endangered in South Australia, Near Threatened in the Northern Territory, and as Vulnerable in Western Australia. At present there is no recovery plan in place for ghost bats, although conservation advice exists as part of their listing under the EPBC Act (Threatened Species Scientific Committee 2016*a*).

Ghost bats in the Pilbara region of Western Australia

The Pilbara region of Western Australia is the centre of iron ore production in the state and, despite its remoteness, is an increasingly industrialised landscape (Environmental Protection Authority 2014; Department of Mines, Industry Regulation and Safety 2021). The region supports an estimated 2000 ghost bats but there has been no robust census to date (Threatened Species Scientific Committee 2016*a*; Fig. 1). The largest colony sizes have been recorded in six historical gold and copper mines in the East Pilbara (Chichester subregion), two of which are now destroyed (Hall *et al.* 1997; Armstrong and Anstee 2000). The remaining four mines have begun to collapse, show evidence of flooding and human visitation (Threatened Species Scientific Committee 2016*a*), and are of continued economic interest to mining companies (e.g. Warrawoona Gold Project; Calidus Resources 2020). Smaller colonies in the Chichester subregion are found in caves (mostly in banded iron formations) and small abandoned adits (e.g. Armstrong and Anstee 2000).

In the Hamersley Range, the deep caves suitable for use as diurnal roosts by ghost bats occur in a variety of banded-iron-formation types (the focus of iron-ore extraction), with many of the known roost sites occurring in Marra Mamba and Brockman Iron formations (Armstrong and Anstee 2000). Armstrong and Anstee (2000) suggested that, in the Pilbara, any cave with sufficient depth could be a potential roost site. While ghost bats use a variety of cave and overhang types in the Pilbara, few of these roost sites support either large numbers of bats or maternity colonies.

The conservation advice for ghost bats (Threatened Species Scientific Committee 2016*a*) lists habitat loss due to mining as the most severe threat they face, and Woinarski *et al.* (2014) predicted that most known roost sites in the Pilbara would be destroyed within the next 30 years if current trends in mining continue. Since then, increasing recognition of the vulnerability of ghost bats to mining activities has seen some ghost bat roosts protected and excluded from mining plans (for example, see Environmental Protection Authority 2018).

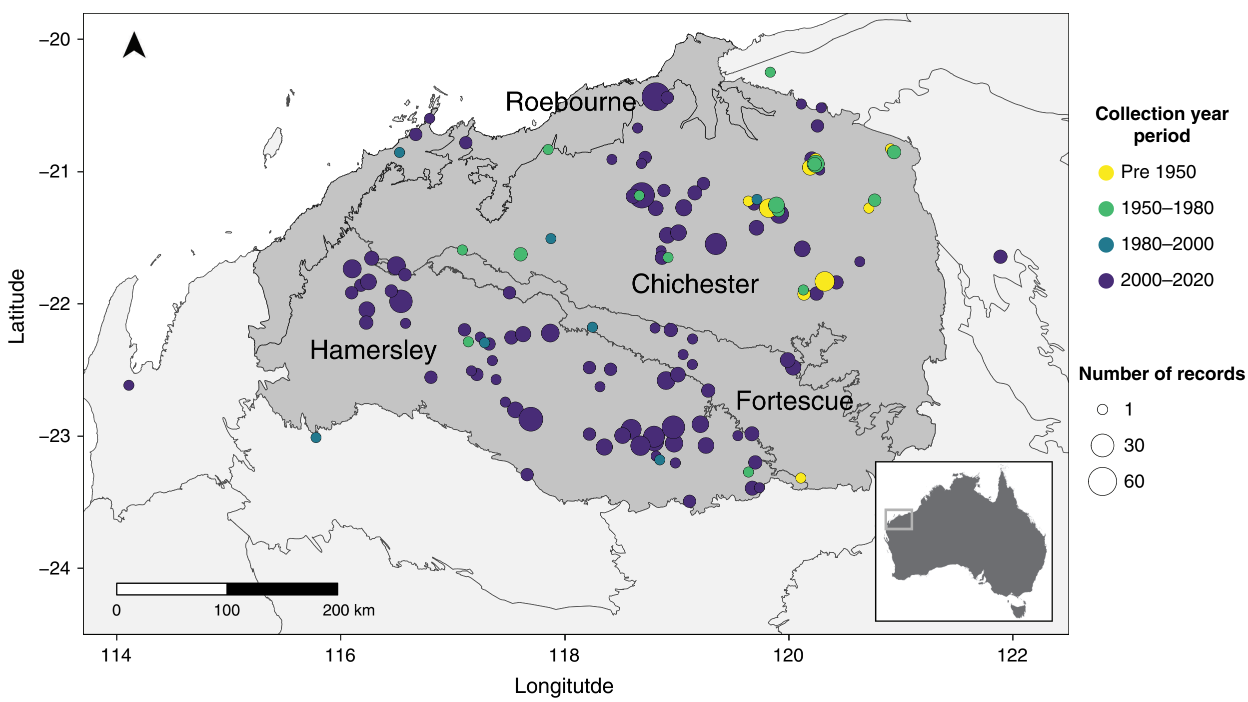

Fig. 1. Map of the Pilbara region with the locations of ghost bat records from the Western Australian Department of Biodiversity, Conservation and Attractions' NatureMap database (https://naturemap.dbca.wa.gov.au). Point size represents the number of records reported within a 20 km radius for each collection year period (specified by colour). The darker grey represents the Pilbara IBRA region, with map borders showing IBRA subregions (Pilbara subregions in black font).

Workshop rationale and process

Their listing as Vulnerable under the EPBC Act means that ghost bats are considered a matter of national environmental significance (MNES), and any development activity likely to have a significant impact upon them requires approval from the Australian Government's Environment Minister (Department of Environment 2013). Historically there has been a conspicuous lack of a coordinated regional effort in the Pilbara to effectively manage species considered MNES (e.g. Armstrong 2010, 2011), with a lack of communication amongst mining proponents creating a significant barrier to achieving the best conservation outcomes. More recently, there has been greater interest amongst all stakeholders to ensure that conservation outcomes for species considered MNES, including the ghost bat, are improved, and there is a growing level of interaction (e.g. Ottewell *et al.* 2017, 2020, 2021).

This increased collaboration has, in part, been fostered through a series of well-attended workshops to develop an agreed set of research priorities for fauna considered MNES in the Pilbara. The research priorities for three MNES species, northern quoll (*Dasyurus hallucatus*), Pilbara leaf-nosed bat (*Rhinonicteris aurantia*) and bilby (*Macrotis lagotis*), have been published (Cramer *et al.* 2016*a*, 2016*b*, 2016*c*). In March 2021, Curtin University hosted a workshop to determine research priorities for the ghost bat in the Pilbara. The workshop process was similar to that outlined in Cramer *et al.* (2016*a*, 2016*b*). We acknowledge that there are more structured approaches to expert elicitation that also consider returns on investment (e.g. Hemming *et al.* 2018); however, the purpose of this workshop was to repeat the successful format of previous workshops and capture the needs of a broad stakeholder group over a defined period of time (i.e. a single day).

The workshop was attended by 53 people: 11 mining industry representatives, 16 environmental consultants, six university-based scientists, nine scientists employed by state or territory governments, and 10 staff of state or federal government agencies who are involved in the environmental impact assessment process. Briefly, speakers gave a series of presentations on the current knowledge of ghost bats in the Pilbara, and on research being undertaken on ghost bats in the Pilbara and other regions. Workshop participants then worked in small groups that contained representatives from each of the affiliations described above. Each group was asked to identify (1) the most significant threats to ghost bats in the Pilbara, and (2) research priorities for ghost bats in the Pilbara. After each of these discussions, the facilitator used each group's feedback and further discussion to create an agreed ranking of both threats and research priorities (Tables 1, 2).

Table 1. The threats to ghost bats in the Pilbara, as ranked by tallying the feedback of workshop participants.

Threat	Rank
Loss of roosts due to destruction by mining and infrastructure development or adit collapse	1
Degradation of foraging habitat	1
Cane toads	2
The cumulative impacts of disturbances and environmental change	3
Impact of climate change on prey availability and cave microclimate	3
Collision with barbed wire fences	3
Human disturbance of roosts	3
Secondary impacts of mining, e.g. dust, noise, vibration, artificial light	4
Competition with, and predation by, feral cats	5
Failure to locate and identify roost caves	6

Several threats to ghost bats in the Pilbara were ranked as of equal importance by workshop participants, and not all workshop participants or groups ranked threats in the same order.

Research priorities for ghost bats in the Pilbara

The research prioritisation for ghost bats was focused on knowledge that will be used to better inform environmental impact assessments and improve the conservation outcomes for ghost bats (Table 2). The ranking of research priorities for ghost bats showed a high degree of concordance with the research priorities for the Pilbara leaf-nosed bat (Cramer *et al.* 2016*b*). Both species are entirely reliant on a limited number of diurnal roost sites, which they often share (Armstrong 2010). As such, some conservation actions are likely to benefit both species.

Priority 1. Habitat use

The ongoing survival of ghost bats requires the protection of two distinct habitats: one for roosting and one for foraging. This dual habitat requirement increases the challenge of understanding how the cumulative impacts of roost destruction and disturbance will affect their colony sizes and regional population. Roosts are given primary consideration in impact assessments because of their critical role for daily survival and breeding (Threatened Species Scientific Committee 2016*a*).

Identify critical diurnal roosts

We propose four categories of roost sites used by ghost bats, ranging from diurnal roost sites that are permanently occupied, through to nocturnal roost sites that are used opportunistically (Table 3). Ghost bats have narrow physiological tolerances but rely on roost sites that provide thermal refuge through stable temperatures, rather than requiring roosts with high humidity (Leitner and Nelson 1967; Kulzer *et al.* 1970; Baudinette *et al.* 2000). This allows

Table 2. Research priorities for the ghost bat in the Pilbara.

Rank	Theme	Research priority	Key questions
1	Habitat use	Identify critical diurnal roosts	Which individual roost sites and/or roost complexes are critical to the survival of ghost bats in the Pilbara?
			How does the location and use of diurnal roosts relate to the use of foraging habitat?
			How does the loss or direct disturbance (e.g. human visitation or vandalism) of roost sites and/or roost complexes affect the movement, survival and breeding success of ghost bats in that area? (Also applicable under priority 3.)
		Identify the characteristics of critical foraging habitat	How does habitat structure and prey type and availability influence how ghost bats use foraging habitat?
			How does their use of foraging habitat vary across seasons and after disturbances (e.g. fire, floods)?
			How does the loss of habitat productivity (e.g. through increased grazing pressure or vegetation clearing) affect prey availability and the foraging activity of ghost bats?
			Do males and females use foraging habitat differently?
2	Distribution, movement and dispersal	Fill knowledge gaps around ghost bat distribution	What is the distribution of the ghost bat in the Pilbara?
		Improve understanding of roost residency, local movement and long-distance dispersal	How long do ghost bats reside at a diurnal roost site or roost complex?
			How do ghost bats move between diurnal roosts at the local scale (e.g. within 10 km)?
			How does local and seasonal movement vary between males and females, and juveniles and adults?
			Which factors influence the timing of long-distance dispersal?
			Is the movement of ghost bats influenced by landscape features, and do certain features act as movement corridors?
3	Population size, persistence and long-term trends	Improved estimates of population size	What is the population size of ghost bats in the Pilbara?
			Which colonies are permanent/maternity colonies and/or are most important in terms of size?
		Increase knowledge of age structure and recruitment rates to inform population persistence	What is the best combination of survey techniques, both traditional and emerging (e.g. faecal DNA analysis, faecal hormone analysis, analysis of sex and age-biased acoustic communication) to determine age structure and recruitment rates?
		Develop techniques to understand long-term population trends	What is the optimal survey protocol that will allow for data on ghost bats to be compared across sites and over time?
4	Impacts from mining, infrastructure development and other human activities	Better understand the local and cumulative impacts of the indirect disturbance of roost sites	How do indirect disturbances from noise, vibrations, artificial lights, vehicle traffic, etc. affect the use of roost sites and/or roost complexes in different geological substrates and in different roost structures?
			If indirect disturbance does affect roost use, does this vary between male and female ghost bats, or with different life stages, especially pregnant or lactating females?
		Assess the effectiveness of artificial roosts	What are the fundamental parameters of natural roosts that need to be replicated in artificial roosts?
			How should chambers be designed so that their internal microclimate can be maintained in the long-term?
			Where should artificial roosts be placed in the landscape?

(*Continued on next page*)

Table 2. (*Continued*)

Rank	Theme	Research priority	Key questions
			Will ghost bats use artificial roosts regularly (i.e. as they would a category 2 cave) and which criteria should be used to measure the success of an artificial roost?
			How can colonisation of artificial roosts be encouraged (e.g. auditory or olfactory cues)?
5	Research for adaptive management of other threats	Entanglement in barbed wire fences	What is the impact of entanglement in barbed wire fences on both colony size and the Pilbara population of ghost bats?
			In what type of habitat is entanglement occurring?
			What are the best alternatives to barbed-wire fences, especially along the movement and foraging corridors of ghost bats?
		Consumption of cane toads	Where in the landscape are the distribution of cane toads and ghost bats most likely to overlap?
			What has been the impact of cane toads on ghost bats in long-invaded and more recently invaded regions?
		Interactions with feral cats	Is predation by feral cats a major cause of mortality in ghost bats?

Table 3. Proposed categories of roost sites used by ghost bats.

Category	Type	Description
1	Permanent diurnal roost	These diurnal roost sites are permanently occupied by ghost bats but the number of individuals present might vary over time. All permanently occupied roosts are assumed to be breeding or maternity sites and should be considered as critical habitat.
2	Regular diurnal roost	Ghost bats occupy these sites regularly over long periods but their presence is not continuous, i.e. most have roosting recorded for >25% of days but they may be abandoned for periods. These sites tend to be deep and have complex internal characteristics. All are assumed to be maternal sites and are therefore critical habitat.
3	Occasional diurnal roost	These sites have internal characteristics that can support roosting, with roosting recorded <25% of days and the site abandoned for long periods. These sites are important for the local, long-term persistence of ghost bats when located as part of a roosting complex that contains category 1 or 2 sites, and should be considered as critical habitat.
4	Nocturnal feeding roost	Most if not all other overhangs and shelters (e.g. adits and culverts) may be used for resting and/or consuming prey during short night-time stays. Scats and/or food scraps are sometimes found. They usually are not structurally suited to maintaining stable temperatures and humidity. These roost sites are not considered critical habitat for ghost bats.

Based upon roost categories and descriptions outlined by Threatened Species Scientific Committee (2016*b*) and Bullen (2020).

ghost bats to use different types of roost sites within a local area, albeit for different reasons and in different ways. Faecal DNA analysis used to identify and track individuals as part of monitoring efforts suggests that ghost bats use roost sites in different ways. Some individuals appear to be transient (only detected in a single cave once during a period of study), while other bats appear to roost in the same one or two caves over multiple years (Ottewell *et al.* 2017, 2021). Some roost sites are used only by transient individuals. This means that sustaining a colony of ghost bats in a local area will likely require more than simply protecting a single permanent diurnal roost, and that the arrangement and number of roost sites, their physical characteristics (e.g. roost architecture and microclimate), and how they function as a roosting complex, must be considered.

Identify the characteristics of critical foraging habitat

Ghost bats are the only Australian bat whose diet contains a significant portion of vertebrate prey. In addition to large insects, they consume frogs, lizards, birds, small terrestrial mammals and other bats (Boles 1999; Richards *et al.* 2008; Start *et al.* 2019). In the Pilbara region, their diet consists mostly of small mammals (including nine species of small insectivorous bats) and birds, but they also eat geckos, skinks and frogs (Claramunt *et al.* 2019; Start *et al.* 2019). Ghost bats have been recorded foraging in all productive habitats in the region, including drainage lines and along riparian corridors, on alluvial plains supporting mulga woodland and tussock grassland, sparse woodland along ridge lines, as well as cave entrances where other bats are hunted (Biologic 2020; Bullen 2020).

The distances that cave-roosting bat species can travel to forage are constrained by the energetic costs of flying and the need to return to a roost (e.g. Rainho and Palmeirim 2011). Habitat fragmentation that increases the distance between diurnal roosts and foraging habitat will likely incur increased energetic costs (Bernard and Fenton 2003). This is a particularly important consideration around permanent/maternity colonies, owing to the likely increased energy requirements of pregnant and lactating females (e.g. Kurta *et al.* 1990). Analyses of forest and woodland cover in Australia found that around 2.9 M ha (2%) of potential or known habitat for ghost bats was lost between 2000 and 2017 (Ward *et al.* 2019).

Landscape-scale disturbances, such as high levels of grazing on pastoral leases, vegetation clearing for development, and changes to the frequency and intensity of fires will alter the spatial and temporal patterns of productivity in the landscape, with likely consequences for prey availability for ghost bats. Climate change also has the potential to change the thermal properties of some diurnal roost sites and the productivity of foraging habitat. The north-west of Australia is predicted to warm faster than other regions, but rainfall is projected to remain largely unchanged (Sudmeyer 2016). At present, only disturbances that cause ghost bats to abandon diurnal roost sites (e.g. from people entering roosts or from the loss of structural integrity of old adits; Armstrong *et al.* 2019) are recognised. There is no clear definition of what constitutes a disturbance to, and significant impact upon, the foraging habitat of ghost bats. An improved understanding of how seasonal changes and landscape disturbances influence prey type and availability, and foraging behaviour, will assist in better defining the types and extent of disturbance that threaten the viability of foraging habitat for ghost bats.

Priority 2. Distribution, movement and dispersal

Understanding how ghost bats move between roost sites, both locally and regionally, will help to determine the effects of roost loss and disturbance, and the likelihood of roost recolonisation after disturbance.

Fill knowledge gaps around ghost bat distribution

The distribution of ghost bats across northern Australia is highly structured, both spatially and genetically (Worthington Wilmer *et al.* 1994, 1999). Much of what we know about ghost bats in the Pilbara arises from fauna surveys undertaken as part of environmental impact assessments for mining and infrastructure developments (Armstrong 2010). Therefore, our knowledge of the location of diurnal roosts and associated foraging habitat could be skewed by the focus of mining proponents on particular land systems and geologies. Predictive models of ghost bat habitat combined with methods that incorporate sampling bias would help to fill this knowledge gap. A species distribution model based on scat samples and other records is currently being developed (K. Ottewell, R. Shaw and R. Thavornkanlapachai pers. comm. 2021). Recent research in the Northern Territory suggests that the playback of the species' 'squabble' calls elicits positive phonotaxis of ghost bats (Hanrahan 2020). This technique is showing promising results as a method for reliable detection of ghost bats in areas where the location of permanent or regular roost sites is not known (L. Ruykys and N. Hanrahan pers. comm. 2021).

Improve understanding of roost residency, local movement and long-distance dispersal

In general, bat activity can be highly variable across temporal scales (hourly, nightly, monthly and yearly; Toop 1985). This temporal variation in activity and diurnal roost occupancy must be considered in both the interpretation of data on bat movements and in the success of management activities aimed at improving conservation outcomes (Milne *et al.* 2005).

Emerging genetic evidence suggests that some ghost bats show high fidelity to a single permanent roost, while others use a 'cluster' of roosts located within several kilometres of each other. In an initial study, Ottewell *et al.* (2017) analysed faecal DNA and tissue samples collected from 18 caves that were monitored on multiple occasions, and found that 16 individuals (11%) were present in a cave for more than one sampling round. More recent work at the South Flank mining precinct (120 km north-west of Newman) found that 37% of the ghost bats recaptured over a 4-year sampling period were resident in the study area for more than 36 months, and some up to 47 months (Ottewell *et al.* 2021). While some bats were resident in a single cave, most bats were detected in both their original cave and other nearby caves over the sampling period, with mean movement distances of around 6 km. A broader analysis of scats collected from 66 caves (some only sampled once), showed that ghost bats mostly used caves within 4 km of each other, and ghost bats within 10 km of each cave site were more highly related (Ottewell *et al.* 2017).

Genetic analyses also suggest that long-distance dispersal is biased towards males, which may disperse more than 100 km (Worthington Wilmer *et al.* 1994; Ottewell *et al.* 2017, 2021). The seasonal timing of long-distance dispersal, at what age this occurs, and how movement patterns vary between males and females are unknown. Recent research by Hanrahan *et al.* (2021) suggest that comparing increases in 'squabble' and 'chirp-trill' vocalisations during the breeding season against an acoustic baseline can be used to indicate the arrival of males and the presence of mating behaviour at maternity colonies. Recently developed molecular sexing markers are being applied to faecal DNA analysis to assess sex-specific differences in cave use and dispersal (Ottewell *et al.* 2020). Analysis of faecal samples for the metabolites of progesterone, an indicator of pregnancy, shows promise as a technique both to identify maternity (i.e. permanent) roosts and understand the behavioural use of roosts by pregnant females (e.g. see Burgess *et al.* 2012).

Ongoing research in the Pilbara and in the Northern Territory is using GPS, and traditional and automated VHF tracking of ghost bats, to determine home range and local movement patterns (C. Knuckey, B. Bullen, L Ruykys and N. Hanrahan pers. comm. 2021). This research will improve our knowledge of how ghost bat movement is influenced by landscape features, such as ridge lines and riparian zones, which may act as movement corridors.

Priority 3. Population size, persistence and long-term trends

The impacts of habitat destruction, roost site disturbance, and the other threats facing ghost bats in the Pilbara cannot be fully understood without current and accurate estimates of their population size and the identification of important colonies.

Improved estimates of population size

Ghost bats are highly sensitive to disturbance of their roost sites, and the intrusion of humans is considered a key threat (Armstrong *et al.* 2019). Roost abandonment and the potential for stress and injury of individual bats raises ethical questions over methods that require entry to caves or the handling of bats (e.g. see Hoyle *et al.* 2001). The comparatively large body size of ghost bats makes it relatively simple to use infrared or thermal video to obtain a verifiable confirmation of their presence and diurnal occupancy at a potential roost site, as well as obtaining an estimate of colony size. Emerging methods such as acoustic lures to capture targeted demographic groups away from the roost entrance may help avoid cave disturbance (Hill *et al.* 2014; Hanrahan 2020).

New techniques for the genetic and hormonal analyses of faecal material are also showing promise as a less-invasive monitoring method that can be used to estimate population size. Scat DNA techniques linked with spatially explicit mark–recapture analyses (e.g. Dziminski *et al.* 2021) can be used to estimate ghost bat abundance. Highly variable microsatellite markers and, more recently, single nucleotide polymorphism (SNP) array markers, are used to genotype faecal pellets and obtain individual DNA fingerprints that function as permanent 'molecular tags', enabling tracking of individuals in space and time under repeated survey. Application of sex-linked markers help to identify permanent (maternity) roosts and to monitor the use of roost sites by different sexes (Augusteyn *et al.* 2017; Ottewell *et al.* 2020).

The genetically effective population size (N_e) is a theoretical estimate of the number of breeding individuals contributing to the next generation and it can provide additional insight into population dynamics. N_e can be estimated from genetic data alone; however, it cannot always be used to extrapolate census population size (N_c) since the direct relationship between effective population size and census population size is not well known for many species (Husemann *et al.* 2016; Mueller *et al.* 2016). Nevertheless, monitoring changes in effective population size over time is an additional approach to assess longer-term population trajectories. Currently N_e estimates are made during faecal DNA monitoring surveys; however, this estimate may be biased since assumptions of sampling from non-overlapping generations cannot be met as the age of individuals depositing scats cannot be determined (Ottewell *et al.* 2017, 2021).

Increase knowledge of age structure and recruitment rates to inform population persistence

Female ghost bats begin breeding at 2–3 years of age and, in the Pilbara, bear one pup in late October to early November each year. Generation time is estimated to be 8 years (Woinarski *et al.* 2014). A better understanding of population demographic parameters such as age structure and reproductive success (or recruitment rates) will assist in developing population viability models to assess the relative extinction risk from direct (e.g. roost destruction) and indirect disturbances (e.g. noise, vibrations, artificial lighting; see priority 4 below). In addition to existing survey methods, novel techniques for estimating animal age from DNA methylation patterns are emerging, and may be useful for obtaining further detail on the age structure of ghost bat colonies (De Paoli-Iseppi *et al.* 2017).

Develop techniques to understand long-term population trends

Long-term monitoring that uses consistent methods will help to differentiate seasonal fluctuations in ghost bat numbers from long-term population trends. Survey effort, especially the effort dedicated to actively search for caves, as well as the survey methods used to detect ghost bats (e.g. acoustic recording, camera traps, nocturnal counts, midden sheeting and mist netting) varies widely (O'Connell and Bullen 2014). The consensus of workshop participants is that consistent protocols for survey and/or monitoring are required, so that data can be compared across sites and over time. Monitoring only a subset of diurnal roost sites may provide poor inference on total population size, the relative importance of any site, and the trajectory of ghost bat numbers. The comparability and sharing of data are crucial for facilitating a detailed understanding of metapopulation dynamics across the Pilbara in the longer term and in response to environmental change. Ensuring that monitoring data are accessible through a centralised database will further assist long-term monitoring efforts.

Priority 4. Impacts of mining, infrastructure development and other human activities on ghost bats

Mining, the development of transport and other infrastructure (e.g. road and rail corridors, wind or solar power generation), and acts of negligence or vandalism can either destroy roost sites (see priority 1) or disrupt ghost bat behaviour. Armstrong (2010, 2011) suggested that the lack of a comprehensive regional management plan was the greatest impediment to the effective conservation of ghost bats in the Pilbara, as there appeared to be no regulatory consideration of concurrent impacts at different sites. Ten years later, few colonies are monitored or managed, and there is no formal integration between mining projects.

Better understand the local and cumulative impacts of the indirect disturbance of roost sites

Noise and vibrations from drilling blasting, and machinery movement, along with artificial lighting and vehicle traffic, have the potential to reduce the occupancy of permanent and regular roosts (Armstrong 2010; Bullen and Creese 2014; Stone *et al.* 2015; Cross *et al.* 2021). Two studies undertaken in the Pilbara found that short-term exploration drilling within 50–85 m of a diurnal roost site did not cause bats to abandon the specific caves under investigation (Armstrong 2010; Bullen and Creese 2014). The authors of both studies, however, cautioned that ghost bats may react differently to the noise and vibration caused by activities other than drilling (e.g. blasting, pad construction by a bulldozer, nearby construction of roads or infrastructure). We do not know how the indirect disturbances described above influence the use of diurnal roost sites and, if a colony abandons a roost site, when they will return. Further research and rigorously designed adaptive monitoring (e.g. see Lindenmayer and Likens 2009) on the secondary impacts of disturbance are required. At present, with relatively few local studies on buffer sizes and noise and vibration thresholds, an empirical determination of disturbance thresholds that trigger a significant response remains a substantial practical challenge.

Assess the effectiveness of artificial roosts

Where the destruction of a diurnal roost site is unavoidable, mining or development proponents may be required to construct an artificial roost to replace it. As with the Pilbara leaf-nosed bat, the benefits of artificial roost creation for ghost bats are yet to be effectively demonstrated. Category 1 and 2 roost sites (i.e. roosts occupied $>25\%$ of days) should not be destroyed with the expectation that the construction of an artificial roost will provide an environmental offset that is ecologically equivalent (Bekessy *et al.* 2010; Cramer *et al.* 2016*a*).

To date, BHP Iron Ore has constructed two artificial roosts specifically for ghost bats (with one artificial roost designed for both ghost bats and Pilbara leaf-nosed bats). One to five ghost bats used the artificial roost at Cattle Gorge for 64 days between October 2018 and May 2020 (S. Wild pers. comm. 2021). Despite considerable effort to consider the size and flight ability of ghost bats, and to replicate the dimensions and microclimate of the destroyed roosts, our understanding of how to construct an effective artificial roost is in its infancy. Questions remain around the placement of artificial roosts in the landscape, the complexity and design of their chambers, the maintenance of their internal microclimate, and their proximity to foraging habitat and ongoing human disturbance. It will be critical to develop criteria for measuring the success of an artificial roost: in terms of the numbers of bats that use the roost and the proportion of time they use it; how the roost is used (e.g. maternal, diurnal, nocturnal); and the environmental impact of the construction. A better understanding of how ghost bats use cave and adit roosts seasonally and in a functional sense (e.g. maternity roosts) might improve the design of artificial roosts (Mering and Chambers 2014).

Priority 5. Research for adaptive management of other threats

Entanglement in barbed wire fences

After habitat loss and disturbance, collision with barbed wire fences is thought to be the most significant threat ghost bats face (Threatened Species Scientific Committee 2016*a*). Ghost bats are known to fly close to the ground while traversing the landscape or foraging for prey (Tidemann *et al.* 1985), which brings them into contact with barbed wire fences that they either fail to see or detect with echolocation (Fig. 2; Armstrong and Anstee 2000). The impact of entanglement on the Pilbara population has not been quantified. Installing conspicuous white nylon wires, white electric fence tapes or metal discs reduces ghost bat collisions with fences (Booth 2006; Maclean 2011) but there has not been any research that quantifies the most effective option. Longer-term, increased understanding of the landscape-scale movement of ghost bats (see priority 2) would allow for alternative fence types to be used in the movement and foraging corridors used by ghost bats.

Fig. 2. A ghost bat caught on a barbed wire fence in the Pilbara. Photo by Thomas Rasmussen (Biologic).

Consumption of cane toads

The introduced cane toad (*Rhinella marina*) has been suggested as a factor in the disappearance of ghost bats from the Riversleigh/Boodjamulla area of north-western Queensland and their decline in Kakadu National Park in the Northern Territory (White *et al.* 2016). Genetic analysis has shown that ghost bats lack the resistance to bufonid toxins found in related species of megadermatid bat in south-east Asia (Shine *et al.* 2016). White *et al.* (2016), however, reported finding cane toad remains in a small proportion of ghost bat scats, and they concluded that some ghost bats may consume cane toads and survive.

Despite workshop participants ranking the consumption of cane toads as the second-most significant threat to ghost bats in the Pilbara, understanding the impacts of cane toads did not rank as highly as a research priority. Cane toads have not yet invaded the Pilbara and there is uncertainty about the potential impacts of cane toads on ghost bats in the region. Projections of how climate change will influence rainfall and temperature in the Pilbara differ, leading to uncertainty about both the pathways of cane toad invasion and the extent of invasion into this semi-arid region (see Cramer *et al.* 2016*b*). Comparison of a species distribution model for ghost bats with a fundamental niche model for cane toads (e.g. Kearney *et al.* 2008) will assist in identifying the areas where ghost bats are most likely to encounter cane toads. Improving our understanding of the impacts of cane toads on ghost bat populations in long-invaded (e.g. north Queensland) and recently invaded regions (e.g. the Kimberley), including dietary analysis, would assist in developing more targeted research questions for the Pilbara.

Interactions with feral cats

There is some evidence that introduced feral cats (*Felis catus*) may prey upon ghost bats at the entrance to diurnal roosts (e.g. several co-authors have observed ghost bat remains at the entrance to roost sites, or temporary abandonment of roost sites following the arrival of feral cats). The relatively low height and narrow entrances of some Pilbara caves can bring ghost bats within reach of feral cats, but it is not clear if predation by cats is a major source of mortality. Dietary studies of feral cats through collection and analyses of their scats would help to better understand the level of this threat to ghost bats.

Conclusions

Collaborative research prioritisation (CRP) has become a popular method to address the science–implementation (knowing–doing) gap (Knight *et al.* 2008; Dey *et al.* 2020). While less structured than large CRP studies that seek to generate discipline- or nation-wide research priorities (e.g. Sutherland *et al.* 2006; Sutherland *et al.* 2013), the species- and region-specific approach of this series of workshops on fauna in the Pilbara has generated highly focussed research questions that can be addressed through targeted studies (Dey *et al.* 2020). The questions generated also address the needs of the environmental regulator and local environmental practitioners.

The persistence of ghost bats in the Pilbara appears to be entirely reliant on a limited number of roost sites (caves and disused mines) that provide diurnal refuge and breeding sites. Very few breeding sites in the Pilbara are protected and adequately managed (Threatened Species Scientific Committee 2016*a*). As with the Pilbara leaf-nosed bat (Cramer *et al.* 2016*a*), the limited information on the ghost bat in the Pilbara means that data sharing, collation and meta-analysis can be part of a collaborative strategy to identify the potential cumulative, regional-scale impacts of development projects that are currently approved on an individual basis.

An excellent and timely opportunity exists to prevent the decline of ghost bats in the Pilbara and ensure their conservation into the future. These efforts will be guided by collaborative, applied research between industry, state government, environmental consultants and academic researchers, using new techniques that build upon the considerable exploratory effort of the past two decades. The research priorities outlined here provide an agreed set of questions that will help guide these ongoing collaborations.

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