Threatened Species Recovery Hub

National Environmental Science Programme

Mitigating cat impacts on the brush-tailed rabbit-rat

Summary of key findings

Hugh Davies

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CHARLES DARWIN UNIVERSITY AUSTRALIA

TIWI LAND COUNCIL

TIWI RESOURCES

Project partners:
This report summarises the main results of a collaborative research program with funding and support from the Australian Government's National Environmental Science Program via the Threatened Species Recovery Hub, the Tiwi Land Council, Charles Darwin University, Tiwi Resources, Tiwi Plantation Partners, the Wettenhall Environment Trust, the Indigenous Land and Sea Corporation, the Northern Territory Government's Department of Environment and Natural Resources and the Australian Research Council (LP170100305).

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Cover image: The Tiwi Land Rangers setting up live traps. Image: Hugh Davies

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Executive summary

Australia is home to the highest rate of mammal extinction on Earth. Worryingly, if current trends of population decline across northern Australia continue, more extinctions are likely. While native mammal populations on the Tiwi Islands remain relatively healthy compared to other areas across northern Australia, recent research has revealed some worrying initial signs of population decline. Given the similarities between the patterns of initial decline on the Tiwi Islands and the patterns of decline that preceded the widespread collapse of native mammal species on mainland northern Australia, as well as evidence that similar factors are involved, it is clear that effective management actions need to be identified and implemented as soon as possible to ensure areas such as the Tiwi Islands remain a refuge for native mammals. However, the decline of native mammals across northern Australia is a result of complex, spatially-variable interactions between a range of factors, including fire and feral animals. As such, before we can develop/implement effective management, we need to better understand the distribution, abundance and status of native mammal populations on the Tiwi Islands, while concurrently improving our understanding of the threatening factors, including feral species and fire. Since 2018, we have conducted field surveys, analysed existing data, and adapted newly developed modelling software to address important knowledge gaps.

Our work (detailed below) supports the view that native mammal populations on the Tiwi Islands have remained relatively healthy compared to most other areas of northern Australia. This is particularly true for native mammal populations on Bathurst Island, including the EPBC-listed (VU) brush-tailed rabbit-rat (*Conilurus penicillatus*). Our research also demonstrated large inter-island variation in feral cat density, with feral cat density being much higher on Melville Island (0.15 cats km^{-2}) compared to Bathurst Island. On Melville Island, feral cat activity and abundance is positively correlated with the frequency of severe fires and the activity of large feral herbivores (buffalo and horse). Our results suggest that reducing the frequency of severe fires and removing feral herbivores may help mitigate the impact of feral cats on native mammal populations, including the brush-tailed rabbit-rat. Importantly, such management would also substantially improve habitat quality. We also outline a modelling framework that we hope will enable a better understanding of the ecological effects of fire management on savanna biodiversity. This will improve our capacity to adapt and refine our approach to fire management across northern Australian savannas.

The current application of prescribed fire management aimed at reducing the severity of fires is an essential management action across the Tiwi Islands. Ideally, such fire management should be accompanied with ongoing monitoring to better understand the associated ecological consequences (both positive and negative). However, the concurrent application of low-intensity fire management with a reduction of feral herbivore populations could be required for the conservation of native mammal populations on Melville Island. The management of feral herbivores on Melville Island should be developed in close collaboration with Tiwi landowners and could be targeted towards specific areas to maximise ecological and cultural outcomes.

These results, as well as other research conducted on the Tiwi Islands over the past eight years, align with our general understanding of native mammal persistence/decline across northern Australian savannas. An integrated and adaptive approach to land management, coupled with a robust optimal monitoring program, would enable the early identification, and inference surrounding future population change of important Tiwi species.

1. Background

The dire state of Australia's mammal fauna

The recent history of mammal extinction on the Australian continent remains an anomaly, with the patterns and severity of loss being markedly different to elsewhere in the world (Woinarski et al., 2015). Given that the Australian continent is very sparsely populated and home to a modern, wealthy society, one might expect somewhat secure biodiversity. However, almost paradoxically, the opposite is true. Australia has experienced an extraordinarily high rate of mammal extinction. So far, 10% of Australia's native terrestrial mammal species have become extinct since European colonisation in 1788 (Woinarski et al., 2015), and many more have disappeared from most of their former ranges and are now at risk of extinction.

Australia's mammal extinctions have been geographically and taxonomically uneven. The most severe population crashes occurred across southern and central Australia, with ground-dwelling mammal species with a body size within the range of 35–5500 g being most susceptible to extinction; so much so that this body size range is now referred to as the 'critical weight range' (CWR). There have been numerous threats implicated in the decline and extinction of native mammal species across Australia, including invasive predators, changed fire regimes, habitat loss and fragmentation, and grazing by feral herbivores (Woinarski et al., 2015).

Declines across northern Australia

Until relatively recently it was assumed that the vast, uncleared savannas of monsoonal northern Australia might be spared the loss of their mammal fauna. However, work since the 1990s has demonstrated that northern Australia's native mammals are experiencing widespread and severe decline (Woinarski et al., 2011), which, if continue unabated, will lead to more extinctions (Geyle et al., 2018). The drivers of the current decline of native mammals across northern Australia have proven difficult to identify and disentangle.

The decline of native mammals in Kakadu National Park was first identified between 1986 and 1993, and was initially attributed to a reduction in groundwater levels (Braithwaite and Muller, 1997). However, by first demonstrating the continuation of these declines following years of above rainfall, Woinarski et al. (2001) suggested that the declines recorded earlier throughout southern and arid Australia were now being recorded in the monsoon tropics. This proposition is supported by evidence that the mammal species exhibiting decline in northern Australia are strongly concentrated in the CWR, suggesting fundamentally similar drivers (Murphy and Davies, 2014). The realisation that the mammal fauna of the vast savannas of northern Australia may not be as secure as once thought stimulated efforts to identify and mitigate the drivers involved.

Over the last decade, a conceptual model has emerged postulating that frequent fire and heavy grazing by feral herbivores have degraded habitats, disrupting both 'bottom-up' (e.g. resource availability) and 'top-down' (e.g. predation) processes, leading to widespread decline in populations of small native mammals (Stobo-Wilson et al., 2020). The gradual westward-spread of the highly toxic, introduced cane toad (*Rhinella marina*) has caused dramatic population declines in native predators across northern Australia (Phillips et al., 2003, Letnic et al., 2008). However, the direct effect of cane toad ingestion is likely restricted to carnivorous mammals, such as the northern quoll (*Dasyurus hallucatus*). As quoll populations were experiencing decline before the toad front arrived (Braithwaite and Griffiths, 1994, Ibbett et al., 2017), and mammals have declined in toad-free areas (Davies et al., 2018), the role of cane toad ingestion in the northern mammal decline is likely only a small part of the story. However, a recent conceptual model of cane toad driven trophic cascade, has proposed a plausible indirect link between cane toads and native mammal decline (Radford et al., 2020b). While invasive grasses such as gamba grass (*Andropogon gayanus*), can cause dramatic changes in fuel loads and fire intensity (Rossiter et al., 2003), the spread of such grasses has been mostly restricted to the Darwin region.

Unfortunately, there are few areas remaining across northern Australia (and across Australia in general) that have not exhibited evidence of native mammal decline (either demonstrated or anecdotal). Currently, only two of Australia's 85 bioregions are considered to support an intact mammal assemblage: the Tiwi Island/Cobourg Peninsula bioregion and the North Kimberley bioregion (Burbidge et al., 2009). While large offshore islands continue to support populations of threatened mammals that have disappeared from the mainland, recent evidence of decline on Melville Island (Australia's second-largest island) suggests it is important to differentiate between areas that are true refuges (i.e. where threatening factors are either absent of effectively managed) and areas that appear as refuges due mainly to productivity driven population resilience.

Sadly, we are witnessing the ongoing decline of the unique Australian mammal fauna. Once widespread species are now persisting in only a handful of areas. If these species are to persist over the long-term, we need to better understand the drivers of decline in order to develop effective management actions.

The Tiwi Islands

The Tiwi Islands are a group of islands located around 80 km north of Darwin. The Tiwi Islands include two main islands, Melville and Bathurst, Australia's second and fifth largest islands respectively, and numerous smaller, uninhabited islands. There has been an unbroken history of occupation and ownership of the Tiwi Islands by the Tiwi people, who possess a distinct culture and language. The Tiwi people have a clear vision for their future:

> *"Our vision is of an independent and resilient Tiwi society built on the orderly and well managed utilization of our natural and human resources through reliance upon our own management, maintenance and protection of unique cultural and natural resource values for the enjoyment and benefit of future generations of Tiwi."*

As a step towards achieving this vision, the Tiwi landowners have determined to use up to 10% of their land for development purposes. This has included the development of a forestry operation across the western half of Melville Island. Apart from this forestry operation, the islands remain largely intact, with minimal land clearing or development.

The islands experience a tropical monsoonal climate with a humid wet season (November–March) in which over 90% of the annual rainfall occurs, followed by a dry season (April–October). There is a substantial gradient in mean annual rainfall, from 1400 mm in the east, to 2000 mm in the north-west. The major vegetation types are savanna woodlands and open forests dominated by *Eucalyptus miniata, E. tetrodonta* and *Corymbia nesophila*, with a predominantly grassy understorey. Shrub density is highly variable, and studies on the mainland have shown that this is influenced by the fire regime (Russell-Smith et al., 2003, Woinarski et al., 2004).

Savanna woodlands are among the most flammable environments on Earth. As such, fire frequency across the Tiwi Islands is very high, but there is significant variation across the islands. A number of introduced mammalian species are present on the islands, including feral cats (Melville and Bathurst), horse (Melville), buffalo (Melville), and pigs (Bathurst and western half of Melville).

The Tiwi Islands are a haven for biodiversity, supporting a high diversity of plants and animals, some of which occur nowhere else on Earth. Importantly, many EPBC-listed threatened species that have suffered widespread population decline in other areas of northern Australia persist in greater numbers on the Tiwi Islands, including the brush-tailed rabbit-rat (*Conilurus penicillatus*, VU), black-footed tree-rat (*Mesembriomys gouldii*, VU), northern brushtail possum (*Trichosurus vulpecula arnhemensis*, VU), red goshawk (*Erythrotriorchis radiatus*, VU), olive ridley turtle (*Lepidochelys olivacea*, VU) and partridge pigeon (*Geophaps smithii*, VU). While native mammal populations on the Tiwi Islands have remained in a healthier state than those on mainland northern Australia, there is evidence of initial decline on Melville Island (Davies et al., 2017, Davies et al., 2018). The similarities between these initial signs of mammal decline on the Tiwi Islands, and those recorded from mainland northern Australia (which preceded the broad-scale species loss) suggests that without effective management, mammal populations on the Tiwi Islands will likely suffer a similar demise to most other areas of Australia. However, before we can develop effective management actions, there remains numerous knowledge gaps that must first be addressed. Over the previous three years, we have conducted a collaborative research program on the Tiwi Islands. Over this time, we conducted field surveys, analysed existing data, and adapted newly developed modelling software to address a number of these knowledge gaps. In doing so, we aimed to increase our capacity to develop and implement informed, and targeted management for species conservation on the Tiwi Islands, and across northern Australia more broadly.

2. Native mammals

Native mammal population density on the Tiwi Islands

Robust estimates of population density increase our ability to understand population change and our capacity to mitigate population decline (Efford, 2004), such as those currently occurring across northern Australia. Recently, advances in statistical modelling have improved our ability to accurately estimate population density. For example, spatially-explicit capture–recapture ('SECR') models take into account both the distribution and movement of individuals in relation to detectors (e.g. traps or motion-activated cameras) to provide estimates of density that are unbiased by edge-effects and imperfect detection (Efford, 2004). Despite their utility, spatially-explicit estimates of population density are rare for northern Australian mammals. This likely reflects, in part, the diminished ability to obtain sufficient data required for these analytical methods due to the catastrophic declines suffered by native mammals across northern Australian savannas that occurred prior to the development of these methods. However, such data can still be obtained for native mammal populations from areas of northern Australia that remain relatively intact (Heiniger et al., 2018, Heiniger et al., 2020). Despite the usefulness of such data, there are currently no estimates of native mammal population density on the Tiwi Islands.

To address this important knowledge gap, we conducted intensive live-trapping at four sites across the Tiwi Islands: two on Bathurst Island (Cape Fourcroy and Ranku) and two on Melville Island (Pickertaramoor and Cache Point) (Figure 1). As we aimed to explore the environmental correlates of native mammal density across the Tiwi Islands, the locations of the four sites were chosen to represent varying combinations of fire frequency, feral cat density and feral herbivore presence (Table 1). The Pickertaramoor and Ranku sites were characterised by extremely high fire frequency, burning, on average, in 81% and 84% of calendar years, respectively, over a 17-year period (2000–2016). The Cache Point and Cape Fourcroy sites were placed in areas with lower fire frequency, burning on average in 38% and 48% of calendar years, respectively, over a 17-year period (2000–2016). Feral cat activity is higher at Pickertaramoor than Cache Point, and exceptionally low at both the Ranku and Cape Fourcroy sites. Feral herbivore activity is also higher at Pickertaramoor than at Cache Point, and absent from Bathurst Island. To investigate the variation in native mammal density across the four sites, we fitted spatially-explicit capture–recapture models using the 'secr' package (Efford, 2020) in the statistical program R (R Development Core Team, 2013).

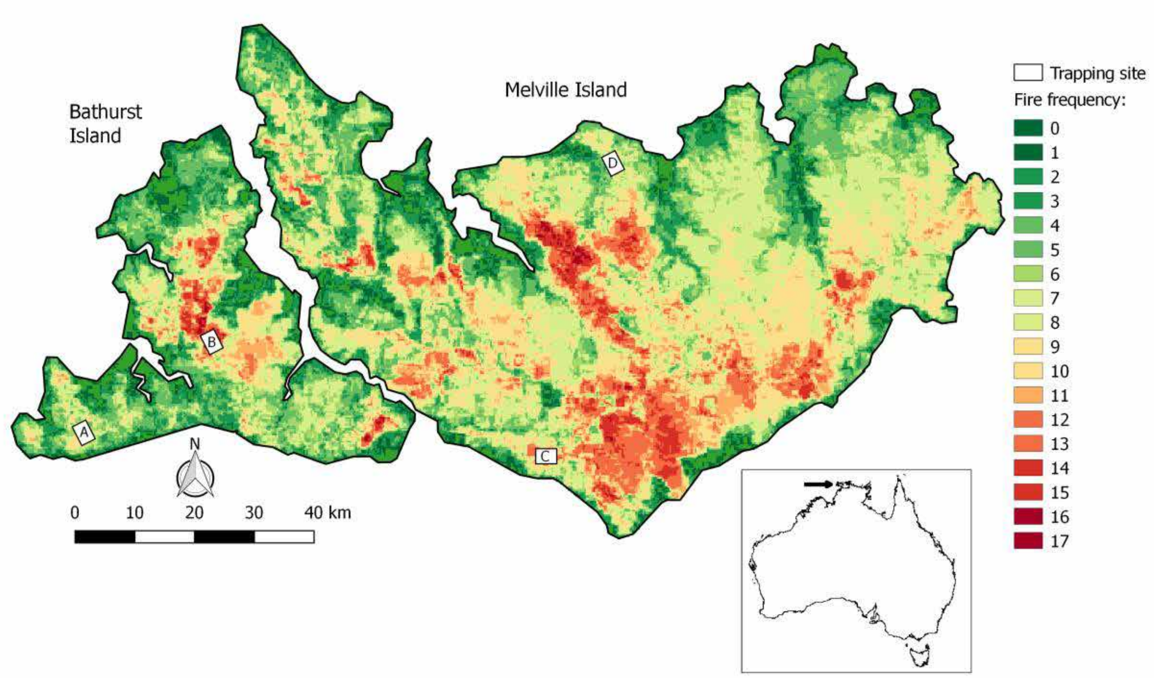

Figure 1: *The location of our four live-trapping sites on the Tiwi Islands (A: Cape Fourcroy; B: Ranku; C: Pickertaramoor; D: Cache Point). The background map indicates MODIS satellite-derived fire frequency (number of times burnt in the 17-year period 2000–2016, inclusive). The location of the Tiwi Islands relative to mainland Australia is also shown (inset).*

From 9,600 live-trap nights, we recorded a total of 365 captures of 154 individual native mammals, from eight species (Table 1). The northern brushtail possum (*Trichosurus vulpecula arnhemensis*) and northern brown bandicoot *(Isoodon macrourus*) were by far the most commonly trapped species, with 202 captures of 77 individual possums and 111 captures of 44 individual bandicoots (Table 1). However, there was considerable variation in the number of captures of each of these species between the four sites. For example, we recorded 81 captures of 30 individual possums at Cape Fourcroy but only 16 captures of 6 individuals at Cache Point. Similarly, captures of the northern brown bandicoot varied from 50 at Ranku to just 3 at Pickertaramoor.

Table 1: *A summary of the sites and species capture counts. The number of individual animals is shown in the parentheses. Dashes indicate where grids were located outside the range of a particular species.*

	Cape Fourcroy	Ranku	Pickertaramoor	Cache Point	Total captures (individuals)
Island	Bathurst	Bathurst	Melville	Melville	
Fire frequency	Low	High	High	Low	
Feral herbivores present?	No	No	Yes	Yes	
Feral cat density	Low	Low	0.15 cats km^{-2}	0.15 cats km^{-2}	
Feral pigs present?	Yes	Yes	No	No	
Northern brushtail possum (VU) *Trichosurus vulpecula arnhemensis*	81 (30)	77 (29)	28 (12)	16 (6)	202 (77)
Northern brown bandicoot *Isoodon macrourus*	19 (7)	50 (18)	3 (2)	39 (17)	111 (44)
Delicate mouse *Pseudomys delicatulus*	0 (0)	14 (5)	1 (1)	10 (8)	25 (14)
Black-footed tree-rat (VU) *Mesembriomys gouldii*	-	-	8 (5)	8 (7)	16 (12)
Pale field-rat *Rattus tunneyi*	4 (1)	3 (2)	0 (0)	0 (0)	7 (3)
Butler's dunnart (VU) *Sminthopsis butleri*	1 (1)	0 (0)	0 (0)	1 (1)	2 (2)
Grassland melomys *Melomys burtoni*	0 (0)	0 (0)	0 (0)	1 (1)	1 (1)
Northern brush-tailed phascogale (VU) *Phascogale pirata*	0 (0)	0 (0)	0 (0)	1 (1)	1 (1)
Total captures (individuals)	**105 (39)**	**144 (54)**	**40 (20)**	**76 (41)**	**365 (154)**

Capture rates were sufficient to estimate population density using spatially-explicit capture-recapture analyses for both the northern brushtail possum and northern brown bandicoot. Variation in northern brushtail possum density varied between the islands, with the estimated possum density on Bathurst Island (1.06 ha^{-1}) significantly higher than on the adjacent Melville Island (0.32 ha^{-1}) (Figure 2). Northern brown bandicoot density varied across all four sites, ranging from 0.04 ha^{-1} at Pickertaramoor to 0.34 ha^{-1} at Ranku (Figure 3).

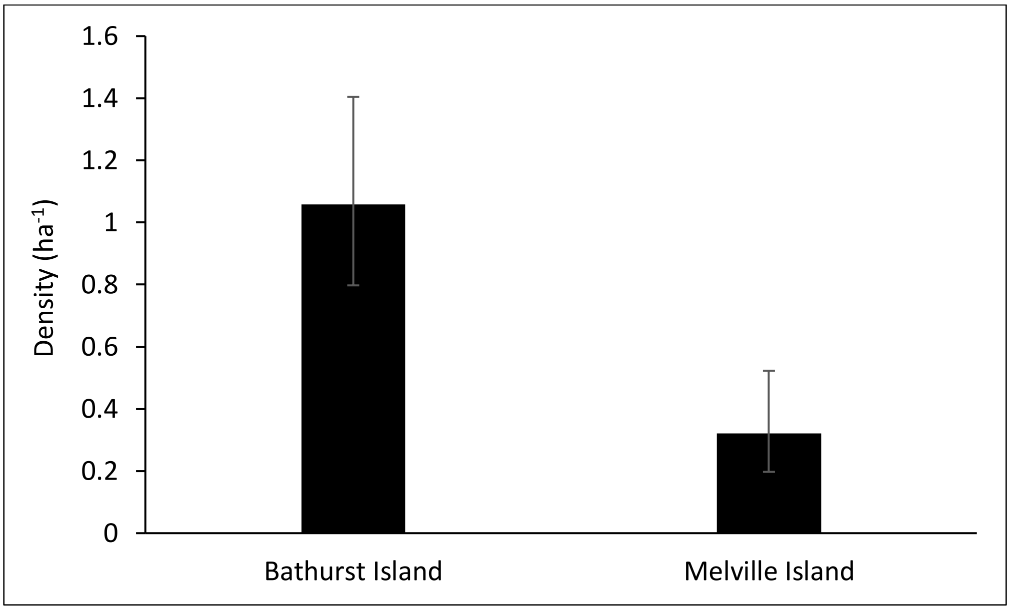

Figure 2: *The mean density of the northern brushtail possum on Melville and Bathurst Islands. Error bars indicate the 95% confidence intervals.*

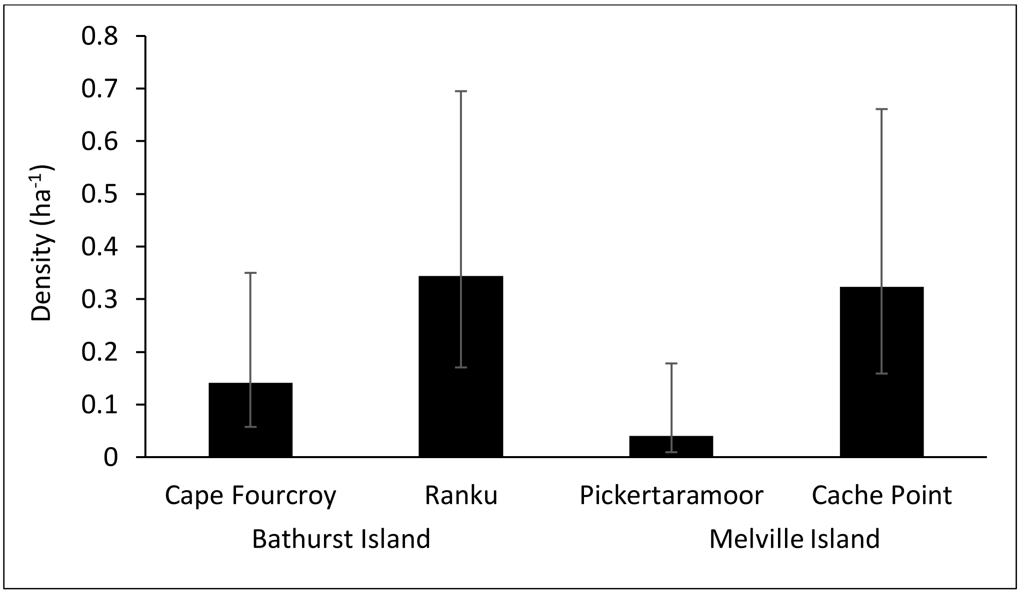

Figure 3: *The mean density of the northern brown bandicoot at each of the four sites across the Tiwi Islands. Error bars indicate the 95% confidence intervals.*

We have provided the first robust population density estimates for the northern brushtail possum and northern brown bandicoot on the Tiwi Islands, one of the last remaining areas in Australia to retain a complete assemblage of native mammals (Burbidge et al., 2009). Our density estimates support the view that populations of these species on the Tiwi Islands have remained relatively healthy compared to adjacent parts of the mainland. Albeit from only four locations, we have provided critical information for identifying and understanding future population change for two species that have suffered marked declines across the Australian monsoon tropics. While the lack of replication limits our ability to draw conclusions regarding the ecological constraints of these mammal populations, our observations provide valuable insight, and align with a recent conceptual model postulating that the persistence of native mammal populations across northern Australian savannas reflects a complex, but spatially-variable interplay of 'bottom-up' (e.g. resource availability) and 'top-down' (e.g. predation) processes.

This has important management implications. For example, as possum and bandicoot populations remain healthy at the very frequently burnt Ranku site, targeted management aimed at reducing fire frequency in this area may be unnecessary and not offer the same benefits to these species as if such management were applied in other areas, such as Pickertaramoor. In other words, our results suggest that the benefits of targeted management actions can vary across the landscape depending on the occurrence and severity of disturbance processes, and the degree to which these are mitigated by landscape productivity. Given limited operational budgets for management agencies, a more spatially-tailored approach to management, may be more effective.

A manuscript describing these results has been published in *Pacific Conservation Biology* (Davies et al., 2021).

A health check of native mammal populations on Bathurst Island

While native mammal populations on the Tiwi Islands have remained relatively intact compared to other areas of northern Australia (Burbidge et al., 2009, Davies et al., 2018), many of the drivers implicated in these declines are present, including feral cats, frequent fire and large feral herbivores. Given the risk that these factors pose, Davies et al. (2018) conducted a health check of native mammal populations on Melville Island in 2015. By comparing native mammal survey data collected in 2000 and 2015 at 82 sites across the island, they demonstrated initial signs of population decline, including a significant decrease in species richness and trap-success. While based on only two-surveys conducted 15 years apart, this study revealed worrying patterns of population decline on Melville Island with similarities to those recorded earlier across areas of mainland northern Australia.

Despite being Australia's fifth largest island, we do not have a clear understanding of the status and distribution of native mammal species across Bathurst Island (2,600 km^2). This lack of understanding is currently limiting the capacity to make informed land-management decisions on the Tiwi Islands, or gauge the appropriate listing of some threatened species under various legislation or on the IUCN's (International Union for Conservation of Nature) Red List of Threatened Species (IUCN, 1996).

To investigate the health of native mammal populations across Bathurst Island, we resurveyed 40 historical sites across Bathurst Island in 2020 that were last surveyed in 2000 (Figure 4). Given the absence of large feral herbivores and a low density of feral cats, we hypothesised that native mammal populations would be doing well compared to Melville Island and mainland northern Australia. At each of the 40 sites, we repeated the live-trapping methods conducted 20 years earlier.

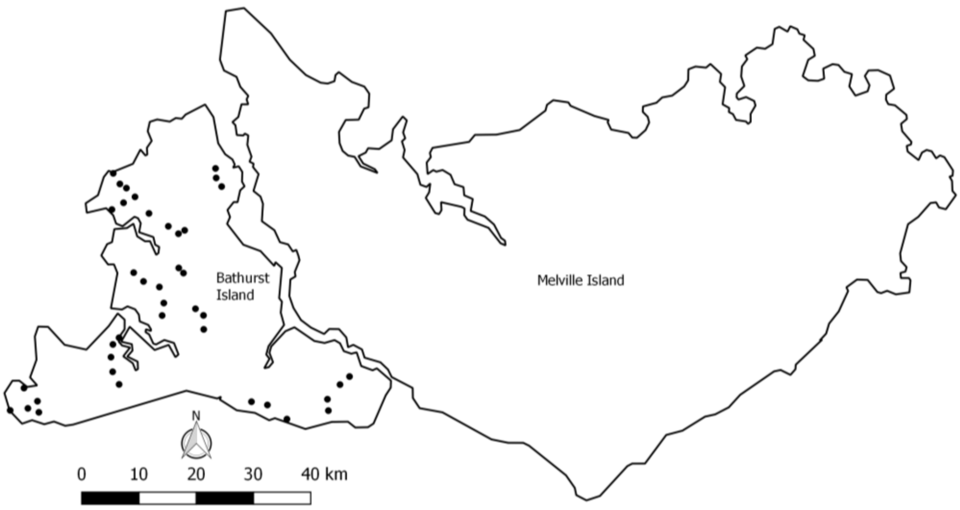

Figure 4: *The location of 40 historical sites (black dots) across Bathurst Island that were resurveyed in 2020.*

To investigate the health of native mammal populations on Bathurst Island we compared trap success and species richness recorded in 2000, with that recorded in 2020. The initial sampling derived trap-success at each site as the total number of animal captures (i.e. not individuals) divided by the number of trap-nights (i.e. 24 traps × 3 nights = 72 trap-nights) (Firth et al., 2006). To enable a direct comparison, we derived trap-success the same way. Native mammals larger than 300 g were exclusively caught in cage traps, while smaller species were only caught in Sherman/Elliott traps. As such, when investigating species-specific changes in trap-success, we first adjusted the number of trap-nights based on the number of traps that might record each species. For example, as northern brown bandicoots were only caught in cage traps, the number of trap-nights for this species was 12 (i.e. four cage traps × three nights). Species richness was calculated as the count of species recorded at each site. As we were comparing native mammal trap-success and species richness at a particular site, with that recorded at the same site 20 years earlier, we used Wilcoxon matched-pairs tests.

The original surveys conducted at these 40 sites in 2000 detected a total of seven native mammal species. In 2020, we detected a total of four species, failing to live-trap grassland melomys (*Melomys burtoni*), pale field rat (*Rattus tunneyi*) or western chestnut mouse (*Pseudomys nanus*) (Table 2). However, the total number of native mammal captures recorded at these sites increased from 116 in 2000, to 150 in 2020. We found no significant change in trap-success ($Z = -1.58$, $p = 0.11$) or species richness ($Z = 0$, $p = 1$); Figure 5). When investigating species-specific changes in trap-success, northern brushtail possum (*Trichosurus vulpecula arnhemensis*) trap-success was 186% higher in 2020 (21.46 ± 2.65) than in 2000 (7.50 ± 2.19; $Z = -3.74$, $p < 0.001$), while grassland melomys (*Melomys burtoni*) trap-success dropped significantly from 0.88 (± 0.48) in 2000 to zero in 2020 ($Z = -2.12$, $p = 0.03$). Trap-success recorded in 2000 and 2020 for northern brown bandicoot (*Isoodon macrourus*), brush-tailed rabbit-rat (*Conilurus penicillatus*), western chestnut mouse (*Pseudomys nanus*), delicate mouse (*Pseudomys delicatulus*) and pale field-rat (*Rattus tunneyi*) was not significantly different (Table 2).

Table 2: *Summary of the changes in native mammal live-trapping results at 40 sites across Bathurst Island in 2000 and 2020.*

Species	Naïve occupancy 2000 (%)	Naïve occupancy 2020 (%)	Change in naïve occupancy (%)	Trap-success 2000 (%) (±SE)	Trap-success 2020 (%) (±SE)	Change in trap success (%)
Northern brown bandicoot (*Isoodon macrourus*)	57.5	42.5	-15	8.96 (1.59)	6.25 (1.42)	-30.25 *ns*
Northern brushtail possum (*Trichosurus vulpecula arnhemensis*)	47.5	82.5	+35	7.5 (2.19)	21.46 (2.65)	+186.13 ***
Grassland melomys (*Melomys burtoni*)	15	0	-15	0.88 (0.48)	0	-100 *
Brush-tailed rabbit-rat (*Conilurus penicillatus*)	7.5	10	+2.5	0.21 (0.13)	0.24 (0.15)	+14.29 *ns*
Western chestnut mouse (*Pseudomys nanus*)	7.5	0	-7.5	0.21 (0.12)	0	-100 *ns*
Delicate mouse (*Pseudomys delicatulus*)	2.5	15	+12.5	0.04 (0.04)	0.42 (0.22)	+950 *ns*
Pale field-rat (*Rattus tunneyi*)	10	0	-10	0.17 (0.08)	0	-100 *ns*

Naïve occupancy was calculated as the percentage of the 40 sites where a species was detected. *ns* = not significant, * = $p < 0.05$, *** = $p < 0.001$. Decreases denoted by -, increases denoted by +.

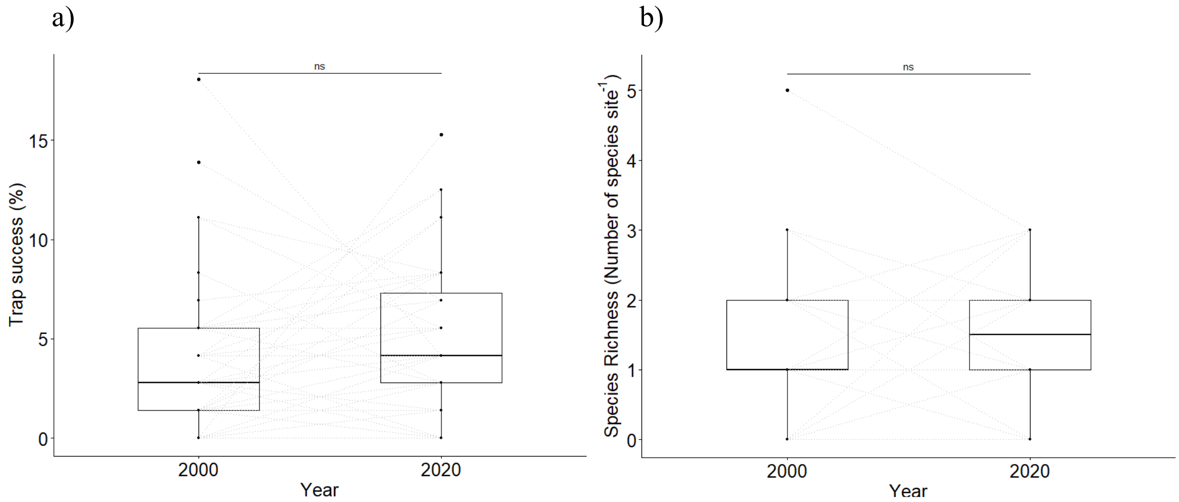

Figure 5: *Summarises site-specific changes in a) trap-success and b) species richness between 2000 and 2020 at 40 sites across Bathurst Island. Faint lines demonstrate changes at individual sites.*

Our inability to detect a change in both trap-success and species richness suggests that native mammal populations on Bathurst Island have not declined since the original trapping was conducted in 2000. This suggests that native mammal populations on Bathurst Island remain healthier than those on Melville Island. This is likely related to the absence of large feral herbivores and low density of feral cats on Bathurst Island. However, it is notable that we failed to detect three species recorded in the original trapping: grassland melomys (*Melomys burtoni*), pale field rat (*Rattus tunneyi*) or western chestnut mouse (*Pseudomys nanus*).

Importantly, we demonstrated no change in trap-success for the EPBC-listed (VU) brush-tailed rabbit-rat (*Conilurus penicillatus*), suggesting that Bathurst Island remains an important refuge for this species. We also note that recent camera-trapping surveys indicate that the brush-tailed rabbit-rat remains widespread across Bathurst Island, and is likely the largest remnant population of this species (H. Davies, *unpublished data*).

The results from this work will be formally written up for publication in a scientific journal. We are currently undertaking a similar survey across Melville Island (to be completed in late 2021), as part of a project funded by the Australian Research Council, in collaboration with the Tiwi Land Council (Linkage Project LP170100305). We intend to include the results from the Bathurst and Melville Island surveys in the same paper.

Investigating potential fire management scenarios with spatially-explicit population simulations

Fire drives the distribution and ecological function of many of Earth's biomes (Parr and Andersen, 2006, Moritz et al., 2014). As such, the development of effective fire management for biodiversity conservation is a globally important issue. However, the effects of fire on biodiversity are controlled by a range of factors that operate and interact across a range of spatiotemporal scales, such as climate, weather, topography, vegetation, herbivory, predation and fire history (Smit et al., 2013, Keyser and Westerling, 2017). Therefore, the effects of fire on biodiversity are often complex, spatially- and temporally-variable, and difficult to disentangle. Not surprisingly, this complexity poses significant challenges when identifying the optimal approach to fire management for biodiversity conservation in fire-prone landscapes.

The highly dynamic nature of fire, the difficulty in replicating 'real-world' fire experiments, and the need to understand population change at large spatiotemporal scales, make computer simulations particularly useful for identifying optimal fire management for biodiversity conservation (Parr and Andersen, 2006). Recently, a feature-rich R package, *'steps'*, has been developed to run spatiotemporally-explicit population simulations (Visintin et al., 2020). Importantly, as *steps* is fully customisable and grid-based, it can more realistically model critical fire-related processes, likely resulting in more robust predictions of the effects of fire than other patch-based software e.g. *RAMAS Metapop* (Akçakaya, 2005). We use *steps* to develop spatiotemporally-explicit population simulations to investigate the marked and ongoing decline of native mammal populations across northern Australian savannas.

An objective of our NESP project was to improve fire management for conservation outcomes. As a step towards achieving this objective, and a better understanding of the ecological consequences of fire management, we aimed to develop a flexible modelling approach with which to investigate how the spatiotemporal application of fire (i.e. management scenarios) impacts savanna biodiversity. We used existing data from the landscape-scale Kapalga fire experiment (Andersen et al., 1998) to develop spatiotemporally-explicit population simulations for three mammal species (northern brushtail possum [*Trichosurus vulpecula arnhemensis*], grassland melomys [*Melomys burtoni*] and northern brown bandicoot [*Isoodon macrourus*]) across the Kapalga area of Kakadu National Park in northern Australia. We simulated how populations were expected to change between 1995 and 2015 in response to the fire patterns observed at Kapalga over this period, and under a hypothetical management scenario of extensive prescribed burning.

Our models predicted a substantial decline in all three species in response to the observed fire regime at Kapalga, suggesting that the fire patterns observed at Kapalga, with the associated mechanisms and interactions with other ecological processes, were not conducive with the persistence of native mammal populations. Our prescribed burning scenario had little effect on the predicted population trajectory of the northern brushtail possum and grassland melomys, but markedly improved the population trajectory of the northern brown bandicoot. These inconsistencies highlight the need for a nuanced approach to fire management across northern Australian savannas, that is tailored to local conditions and management objectives. Our modelling approach provides a basis for identifying fire patterns that are beneficial for conserving biodiversity, across a broad spectrum of ecotaxonomic groups, thereby increasing our capacity to establish clear targets for prescribed fire management. Importantly, this approach is flexible and can be easily adapted to other fire-prone ecosystems.

These results have been published in *Journal of Applied Ecology* (Davies et al., 2020b).

3. Feral animals

Feral cat population density on the Tiwi Islands

Despite the contribution of feral cats to the ongoing collapse of native mammal populations across northern Australian savanna landscapes, we have limited understanding of the processes that constrain feral cat population density in this system (as well as across Australia more broadly). For example, while fire and grazing are important drivers of feral cat populations, as these processes are near ubiquitous across northern Australian savannas, it is often difficult to disentangle the extent to which these processes may influence cat populations in the absence of the other. Addressing such knowledge gaps is a crucial step towards both understanding and mitigating the impacts of feral cats, and is therefore particularly important for the large islands off northern Australia that have remained as strongholds for many species vulnerable to cat predation.

While the Tiwi Islands remain a stronghold for numerous species that are vulnerable to predation by cats, there are worrying initial signs of decline for the northern brown bandicoot (*Isoodon macrourus*), black-footed tree-rat (*Mesembriomys gouldii*), and brush-tailed rabbit-rat (*Conilurus penicillatus*) (Davies et al., 2018), with evidence that cats have contributed to the decline of at least one species (brush-tailed rabbit-rat) (Davies et al., 2017). Importantly, while fire activity is spatially variable across both Melville and Bathurst Island, feral herbivores are only present on Melville Island. As such, these large adjacent islands, provide a useful 'natural experiment' where we can investigate how feral cat density varies under different combinations of fire frequency, and feral herbivore presence. To increase our understanding of the ecological constraints of feral cat populations across northern Australian savannas, we aimed to obtain robust estimates of feral cat density from across Melville and Bathurst Island. We surveyed feral cats at four locations: one with high fire frequency with no feral herbivores, one with low fire frequency with no feral herbivores, one with high fire frequency with feral herbivores, and one with low fire frequency with feral herbivores.

To estimate the density of feral cats, we deployed four grids of motion-activated cameras (camera-traps) across the Tiwi Islands: two on Melville Island (Pickertaramoor and Cache Point) and two on Bathurst Island (Ranku and Cape Fourcroy) (Figure 6). Each camera-trap grid consisted of 14 rows of five camera stations (70 cameras in total) spaced between 400 and 600 m apart, covering an area of approximately 13 km^2. Grids were deployed for between 61 and 64 consecutive days with cameras operating continuously.

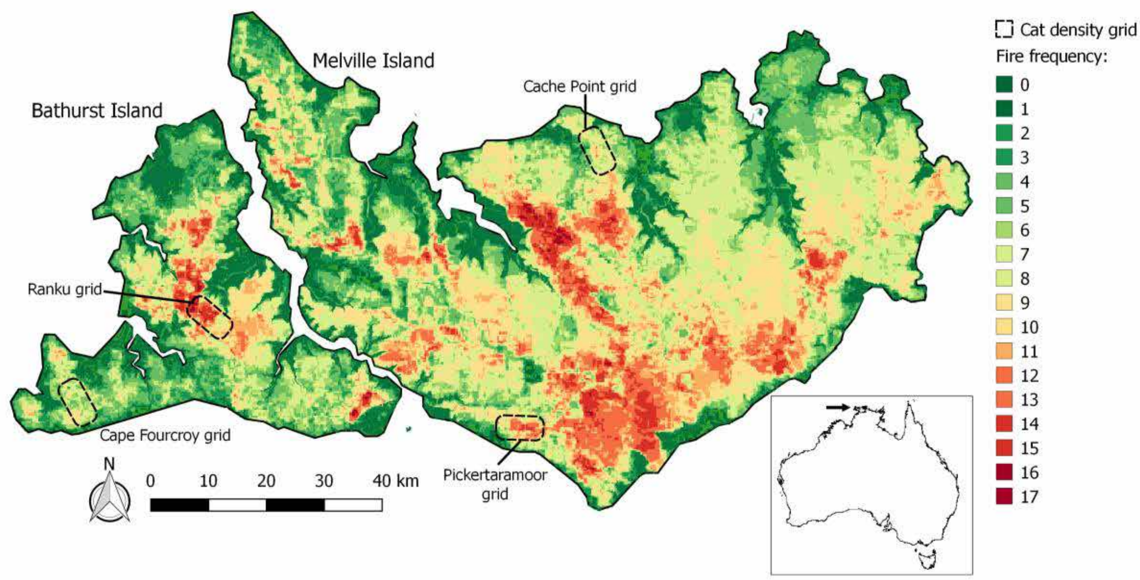

***Figure 6:** The location of the four grids of camera-traps deployed to estimate the density of feral cats on the Tiwi Islands. The MODIS satellite-derived fire frequency across the Tiwi Islands (number of times burnt in the 17-year period 2000–2016, inclusive), and the location of the Tiwi Islands relative to mainland Australia are also shown.*

Individual cats were identified by unique pelage markings by three independent observers. Discrepancies between observers were reviewed until a consensus was reached. Detections of cats which could not be identified to the individual level were omitted from the analysis.

We recorded 26 detections of 10 individual cats on Melville Island, but did not detect any cats on Bathurst Island. Overall, the rate of feral cat detection was very low. From a total of 17,360 camera-trap nights, feral cats were detected at a rate of only 1 cat detection per 667 camera-trap nights. Of these cat detections on Melville Island, 21 (81%) were recorded on the Pickertaramoor grid, with the remaining five (19%) recorded at Cache Point (Table 3). Of the 21 cat detections at Pickertaramoor, there was a total of 18 detections of seven individually identifiable cats. Of the cat detections at Cache Point, there were three individually identifiable cats that were each only recorded once.

Table 3: *A summary of the camera-trap survey data recorded at each of the four grids across the Tiwi Islands. Dashes indicate where grids are located outside of the current range of a particular feral species.*

	Pickertaramoor	Cache Point	Ranku	Cape Fourcroy
Island	**Melville**	**Melville**	**Bathurst**	**Bathurst**
Fire frequency	High	Low	High	Low
Other feral animals detected	Horse, buffalo	Buffalo	Pig	Pig
Feral herbivore nightly detections	214 (134 buffalo, 80 horse)	156 (all buffalo)	-	-
Dingo nightly detections	51	25	36	12
Pig nightly detections	-	-	1	23
Number of cameras	70	70	70	70
Survey duration (days)	62	61	61	64
Number of cat detections	21	5	0	0
Number of identifiable cat detections	18	3	0	0
Number of unidentifiable cat detections	3	2	0	0
Number of identifiable cats	7	3	0	0

Using spatially-explicit capture–recapture ('SECR') models, we estimated feral cat density on Melville Island to be 0.15 cats km^{-2}. Using simulations, we predicted that if cat density on Bathurst Island was equal to that on Melville Island, we would have expected to have record 27.9 detections of 9.9 individual cats. Our results, coupled with other recent surveys, suggest that the density of cats is much lower on Bathurst Island than the adjacent Melville Island. This conclusion has been further strengthened by recent (2020) surveys across Bathurst Island (described in Section 2: Native mammals, above). Arrays of five motion-activated cameras were deployed for five weeks at 40 sites. Zero cat detections were recorded. In contrast, our 2015 survey of 88 sites on Melville Island, using the same five-camera arrays deployed for five weeks, detected cats at 29.6% of sites (Davies et al., 2020a).

The three largest islands off northern Australia (Bathurst Island, Melville Island and Groote Eylandt) have all remained as strongholds for many species that are vulnerable to feral cat predation. Compared to Melville Island (and areas of mainland northern Australia), feral cat density appears to be particularly low on Groote Eylandt (Heiniger et al., 2020) and Bathurst Island. This is despite both these islands supporting healthy populations of small native mammals (i.e. a preferred prey type of feral cats). The low feral cat density on these islands may be related to the absence of feral herbivores from both of these islands resulting in reduced prey accessibility, though further research is needed test this hypothesis. Unfortunately, cat eradication is currently not a feasible option for any of these islands. However, there is growing evidence that enhancing understorey vegetation density, through the concurrent management of fire and feral herbivores, could help mitigate the impact of feral cats on northern Australian savanna biodiversity.

These results have been published in *Pacific Conservation Biology* (Davies et al., 2021).

Feral cat activity/abundance on Melville Island

Earlier work demonstrated strong spatial variation in feral cat activity/detections across Melville Island, with areas characterised with a higher probability of cat detection correlating with contraction of the threatened brush-tailed rabbit-rat (Davies et al., 2017). However, a key unresolved question is what controls that geographic variation in the activity of feral cats. We analysed existing data collected at 88 sites in 2015, to explore the variation in the activity and abundance of feral cats across a range of biophysical gradients on Melville Island. We tested the hypothesis that feral cat activity and abundance is highest in areas of frequent, high-severity fires, and high feral herbivore activity.

Feral cats were recorded at 26 out of the 88 sites (29.6%), on 39 separate 24-hour sampling occasions. At sites where feral cats were detected, the mean number of sampling occasions on which they were detected was 1.5 (range = 1–4). We found that that the frequency of high-severity fires and herbivore activity were the only clear correlates of feral cat activity and abundance. Both of these variables were positively correlated with feral cat activity (Figure 7) and abundance (Figure 8).

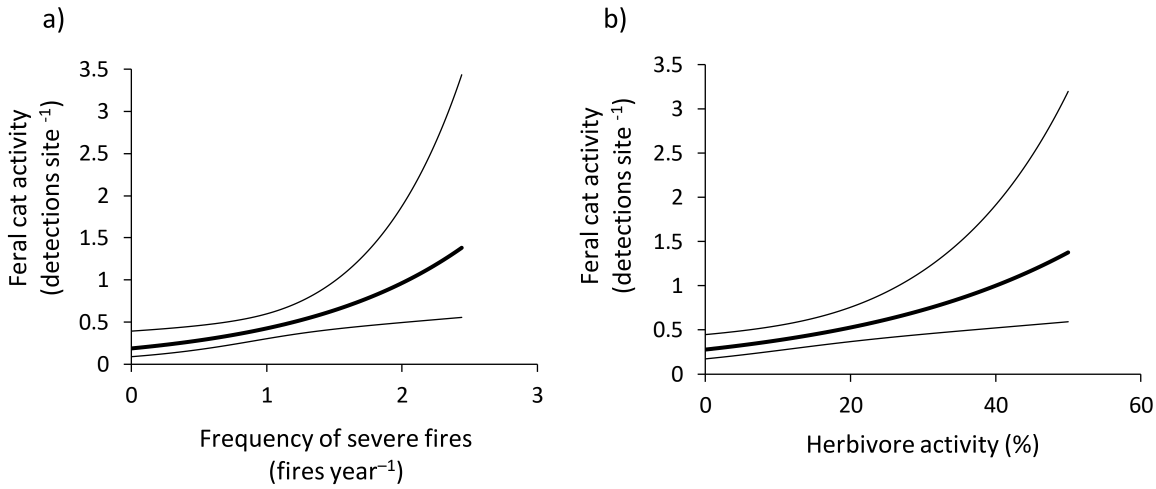

Figure 7: *Modelled relationship between feral cat activity and a) the frequency of severe fires and b) herbivore activity. Thin lines indicate 95% confidence intervals.*

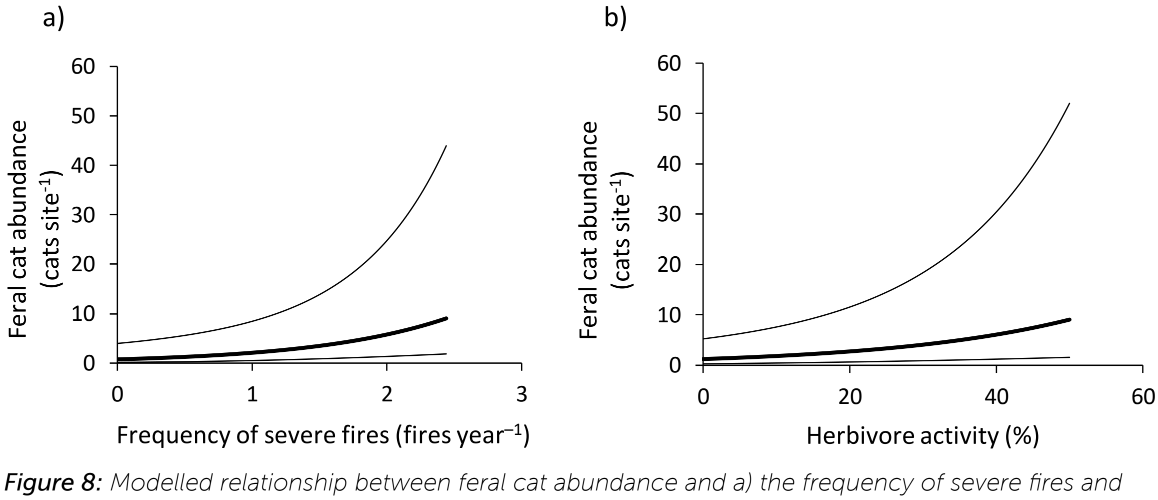

Figure 8: *Modelled relationship between feral cat abundance and a) the frequency of severe fires and b) herbivore activity. Thin lines indicate 95% confidence intervals.*

We have demonstrated that on Melville Island – a part of northern Australia that has retained a diverse assemblage of small mammals, yet has experienced significant mammal declines in recent decades – high feral cat activity and abundance is associated with frequent high-severity fires and high feral herbivore activity. This finding contributes to the growing body of research suggesting that in northern Australian savanna landscapes, disturbances such as high-severity fire and heavy grazing by feral herbivores may offer significant advantages to feral cats. Importantly, both fire severity and the density of feral herbivores can feasibly be manipulated through management actions; in contrast, the direct control of feral cats remains notoriously difficult and expensive, especially in the tropical savannas (Woinarski et al., 2019).

These results have been published in Wildlife Research (Davies et al., 2020a).

4. Synthesis

Management and policy guidelines

Overall, the results outlined in the above sections, align and support the current conceptual understanding of native mammal decline in northern Australian savannas: inappropriate fire regimes (frequent, intense fires) and grazing by feral herbivores disrupt the functioning of savannas by influencing bottom-up (resource availability) and top-down (predation) processes. These disruptions are influenced by broad-scale patterns of landscape productivity, which bolsters population resilience in more productive areas. As a result, mammal declines have been most evident in the lower rainfall areas of inland northern Australia, and least evident in high rainfall productive areas. Given the Tiwi Islands are a productive landscape, receiving the highest average annual rainfall in the Top End, the observation that native mammal populations remain relatively healthy on these islands aligns with the broad-scale patterns of mammal decline/persistence across northern Australia.

Importantly, our research has also demonstrated finer-scale variation across the Tiwi Islands in both the health of native mammal populations, and the density/activity of feral species. These results also support the current conceptual understanding of native mammal decline in northern Australian savannas. This new information has important implications for management aimed at conserving native mammal populations on the Tiwi Islands. Here, we discuss our results to make recommendations of potential management and policy options for native mammal conservation on the Tiwi Islands.

Fire management

Fire management on the Tiwi Islands currently involves the island-wide application of low-intensity prescribed fire in the early dry season (i.e. before July 31st). This approach to fire management is primarily driven by the economic potential of the carbon credits generated by reducing the frequency and extent of fires occurring in the late dry season (i.e. after July 31st). An objective of this our research program was to better understand whether this approach to fire management is conducive with the persistence of native mammal populations on the Tiwi Islands.

This application of low-intensity prescribed fire management is currently applied across Bathurst Island, where mammal populations appear to be among the healthiest across northern Australia, and where population density of northern brushtail possum and northern brown bandicoot remain high (even in an area the experiences very frequent low intensity fire). This suggests that such fire management may be compatible with long-term population persistence. However, this may only be evident in productive areas with no feral herbivores and a low density of feral cats.

There remains little direct evidence that prescribed low-intensity fire management that is specifically aimed at generating carbon credits is beneficial for native mammals (Corey et al., 2019). However, there are examples (albeit only a few) where prescribed burning in the early dry season has benefited northern Australia native mammal populations (Legge et al., 2011b, Radford et al., 2020a). Conversely, there is abundant evidence (both correlative and experimental) that frequent, high-intensity fires negatively impact native mammal populations (Andersen et al., 2005, Legge et al., 2008). It is therefore intuitive that the application of prescribed low-intensity fire is likely to have less of an impact than a fire regime characterised by frequent, high-intensity late-dry season fires, which would otherwise occur across the Tiwi Islands in the absence of early-dry season fire management. As such, despite being motivated by the generation of carbon credits (rather than specifically biodiversity conservation), the current approach to prescribed low-intensity fire management on the Tiwi Islands remains a critical land management tool.

However, there is capacity to better understand and refine the current application of prescribed fire across the Tiwi Islands to maximise the benefits for biodiversity. For example, the development of a carefully designed monitoring program across the Tiwi Islands, would increase our ability to identify and understand population change in response to fire, enabling a more adaptive management approach. It may be that a more strategic placement of fires that reduces the total annual area burnt could afford greater benefits for biodiversity. Importantly, the grid-based modelling framework we adapted to northern Australian savannas will support this. We recommend that such interrogation of the impacts of prescribed fire management go beyond native mammals, and include as many ecologically and culturally important species as possible.

Concurrent management of fire and feral herbivore populations

While prescribed low-intensity fire management remains a critical land management tool across the Tiwi Islands, in some areas, the conservation of native mammal populations may require additional management actions. Research from the Kimberley region of north-western Australia has demonstrated that investment in fire management with the goal of conserving small mammal populations may be ineffective without the concurrent management of other factors, such as feral herbivores (Legge et al., 2019). If this is also the case on Melville Island, prescribed low-intensity fire management may not be enough to conserve native mammal populations, and that other management actions might be required (in addition). Such other management actions include the management of feral herbivores and feral cats.

The management of feral herbivores has been shown to benefit native mammal populations in northern Australian savannas (Legge et al., 2011a, Legge et al., 2019). These benefits are thought to reflect a reduction in post-fire predation of native mammals due to the faster recovery of ground-layer vegetation, as well as improved habitat quality (compared to areas where feral herbivores are not managed). Our research demonstrating the preference of feral cats for areas with frequent severe fires and high feral herbivore activity, suggests that on Melville Island, the concurrent application of low-intensity prescribed fire and a reduction of buffalo and horse abundance, could help mitigate the impact of feral cats. This approach to management would substantially improve habitat quality. It is important to note that feral herbivores (particularly buffalo) are an important food source for Tiwi people. As such, the eradication of buffalo is unlikely to have community support. It is imperative that management actions reflect and respect the values and aspirations of Tiwi people. Future plans to manage feral herbivores on Melville Island should be developed in close collaboration with Tiwi landowners. Potentially, feral herbivores control could be targeted towards specific areas to maximise ecological and cultural outcomes.

As the direct control of feral cats (via toxic baiting, shooting and trapping) remains difficult and expensive, its efficacy as a viable approach for the broad-scale conservation of native mammals across the Tiwi Islands remains unlikely. However, we note that the efficacy of such management has not been investigated on the Tiwi Islands and may be a useful and necessary option in the future, or in certain localised situations, or in concert with other targeted management actions, such as the removal of large feral herbivores.

Stronger cat ownership regulations

While the direct control of feral cats remains difficult and expensive, there are achievable actions that can be implemented in Tiwi Island communities to reduce the impact of feral cats. Stronger pet cat ownership rules and regulations could include: restricting the ability of residents to keep cats as pets, requiring pet cats to be de-sexed, and requiring pet cats to be kept indoors (i.e. restricted from roaming). This may be particularly important on Bathurst Island, where feral cats occur at very low densities, yet pet cats are kept in the main community of Wurrumiyanga (Kennedy et al., 2018). The enforcement of pet ownership rules and regulations should be preceded with community awareness campaigns to inform people of the risks that pet cats can pose to native Tiwi wildlife.

5. Conclusion

The results outlined in this report, as well as other research conducted on the Tiwi Islands over the past eight years, align with our general understanding of native mammal persistence/decline across northern Australian savannas. The demonstrated differences in native mammal populations and feral species between Melville and Bathurst Island, suggests an island-specific approach to management may be beneficial. On Bathurst Island, given the health of native mammal populations, the absence of feral herbivores and the low density of feral cats, the current application of low-intensity prescribed fire management may be sufficient to conserve native mammal populations. On Melville Island, the concurrent management of both fire and feral herbivores would likely mitigate the impact of feral cats while improving habitat quality. This approach to management should be coupled with a robust optimal monitoring program, enabling the early identification, and inference surrounding future population change of important Tiwi species.

Research papers arising from this project:

Davies, H. F., Maier, S. W. & Murphy, B. P. 2020a. Feral cats are more abundant under severe disturbance regimes in an Australian tropical savanna. *Wildlife Research*, 47, 624-632.

Davies, H. F., Tiwi Land Rangers, Nicholson, E. & Murphy, B. P. 2021. Northern Brown Bandicoot (*Isoodon Macrourus*) and common brushtail possum (*Trichosurus Vulpecula*) density on the Tiwi Islands: insights and implications. *Pacific Conservation Biology*.

Davies, H. F., Tiwi Land Rangers, Rees, M. W., Stokeld, D., Miller, A. C., Gillespie, G. R. & Murphy, B. P. 2021. Variation in feral cat density between two large adjacent islands in Australia's monsoon tropics. *Pacific Conservation Biology*.

Davies, H. F., Visintin, C., Gillespie, G. R. & Murphy, B. P. 2020b. Investigating The effects of fire management on savanna biodiversity with grid-based spatially explicit population simulations. *Journal of Applied Ecology*.

* Penton, C. E., Davies, H. F., Radford, I. J., Woolley, L. A., Tiwi Land Rangers & Murphy, B. P. Submitted. A hollow argument: understorey vegetation and disturbance determine abundance of hollow-dependent mammals in an Australian tropical savanna. *Frontiers In Ecology And Evolution*.

*submitted for publication only (not yet accepted)

The project has also contributed to publications in collaboration with the NESP Northern Australia Environmental Resources Hub:

Stobo-Wilson, A. M., Stokeld, D., Einoder, L. D., Davies, H. F., Fisher, A., Hill, B.M., Mahney, T., Murphy, B. P., Stevens, A., Woinarski, J. C. Z., Bawinanga Rangers, Warddeken Rangers, Gillespie, G.R. 2020. Habitat structural complexity explains patterns of feral cat and dingo occurrence in monsoonal Australia. *Diversity And Distributions*, 26, 832-842.

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Research factsheets from this project:

Status of Tiwi Island mammals and lessons for management.
https://www.nespthreatenedspecies.edu.au/media/bqygdrk2/1-1-12-tiwi-island-mammals-findings-factsheet_v4.pdf

Cats, fire and small mammals on the Tiwi Islands.
https://www.nespthreatenedspecies.edu.au/media/nbepcg2e/1-1-12-mammals-on-tiwi-factsheet_web.pdf

Keeping our animals safe on the Tiwi Islands. (in prep.)

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Further information:

http://www.nespthreatenedspecies.edu.au

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Threatened Species Recovery Hub

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