The occurrence, relative abundance and environmental associations of small terrestrial mammals in the Northern Kimberley, Western Australia

Liberty Olds

A thesis submitted in total fulfilment of the requirements for the degree of

Doctor of Philosophy

School of Biological Sciences

Faculty of Science

THE UNIVERSITY of ADELAIDE

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This thesis is dedicated to my parents

Lynette Olds & Graham Olds

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Declaration

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution in my name and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide.

This thesis presents an original and independent piece of research. All significant aspects of analysis and interpretation of results were done by myself. The thesis is presented as a series of papers. Collaborations have been indicated by the co-authorship of these papers as follows: 1) Bill Breed and David Taggart were included in recognition of the contribution they have made as my supervisors; 2) Jim Reside, George Madani, Alexander Dudley, Henry Cook, Brendan Schembri, Christopher Jackson, Tamara Waina, Ernie Boona, Sally Potter, Raz Martin, Nicholas Evans and Brian Charles were include in recognition of their field support across multiple years and 3) Cecilia Myers was included in recognition of her expert advice and land management responsibly of the study sites. These contributions in no way effect the originality or my overall contribution to the thesis.

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> “ Hard work spotlights the character of people: some turn up their sleeves,
> some turn up their noses, and some don’t turn up at all” *Sam Ewing*

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Thesis Abstract

This study examines the distribution and abundance of the small terrestrial mammal fauna (non-volant, <2kg) in the Northern Kimberley bioregion, Western Australia. This region is considered 'pristine' as there have been no known recent mammal extinctions, and cane toads have not yet extensively invaded the region. This study was undertaken on two pastoral stations, Doongan and Theda Stations, which cover a combined area of over 6,650 km^2 . These stations have never previously been surveyed for the occurrence of small mammals. The investigation describes the presence, abundance and environmental relationships of the small mammal species on these stations. The records obtained in this study fill a significant gap in knowledge of the distribution and relative abundance of the small mammal species in the Northern Kimberley region. The results are compared to the small mammal fauna on three adjacent national parks, as well as to those of the broader region of northern Australia.

Extensive trapping surveys of small mammals were undertaken on the two properties. However, only 15 of the 27 small mammal species known to occur in the Northern Kimberley were detected. Four species were commonly found (*Pseudomys nanus*, *Rattus tunneyi*, *Zyzomys argurus* and *Sminthopsis virginiae*). Six other species were detected, but less frequently (*Leggadina lakedownensis*, *Pseudomys delicatulus*, *Pseudantechinus ningbing*, *Dasyurus hallucatus*, *Isoodon macrourus* and *Petropseudes dahli*). The other five species were only detected occasionally (*Melomys burtoni*, *Pseudomys johnsoni*, *Hydromys chrysogaster*, *Planigale maculata* and *Petaurus breviceps*). The trapping success rate was found to be generally low, suggesting that populations were at low density. This indicates that the abundance and distribution of the small mammal fauna may be reduced from what would have occurred in the recent past.

Environmental assessments identified 14 broad habitat types that were surveyed for small mammals across the two stations. The abundance and occurrence of small mammals in these habitats was determined. Temporal changes in trap success were evident across the nine year study period. The influence of broad-scale environmental variables on the composition of the small mammal community was examined using a relatively new modelling tool, the *mvabund* package. The environmental variables partially explained the variation seen across the annual survey efforts. The influence of fire and rainfall variation may have created changes in landscape productivity which, in turn, influenced the small mammal community's composition. Land systems, which describe patterns of vegetation, topography and soils, were also associated with community composition. These systems may indicate the likelihood of species being present within the small mammal community, whilst environmental variables, such as fire and rainfall, influence the species' ability to persist, or vary, in relative abundance.

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Chapter 1
General introduction

There is more specific information: a jump-up place is wherever a rise happens to cut through the plains.
Then: this part of the Kimberley is Wandjina country.
All Wandjina country is either umangat, the stone itself or a range; or memangat, sandstone country;
or garawit, an area of pebbles, or ngallarra, grass country.

David Mowaljarlai and Jutta Malnic
Yorro Yorro: Everything standing up alive

1.1 Introduction

The Northern Kimberley (NOK) bioregion is recognised for its biodiversity value (Carwardine *et al.* 2011). Despite this, research on the small mammal fauna in the region is scarce. Knowledge is based upon few studies, with records being predominantly obtained from three major national parks (McKenzie *et al.* 1975a; McKenzie *et al.* 1975b; Bradley *et al.* 1987; Start *et al.* 2007). Other localities within this region have not been comprehensively investigated and there is limited knowledge regarding the occurrence of many of the small terrestrial mammal species (Turpin 2015). There is also a paucity of habitat and ecological information for many of the species known to occur in the region.

This study focuses on the small mammal fauna of two pastoral stations, Doongan and Theda Stations, situated in the NOK bioregion. The small mammal fauna has not previously been documented for these stations. For the purpose of this study, small mammals have been classified as terrestrial (non-volant) species that weigh <2kg.

The NOK is dominated by tropical savanna, a biome which extends across northern Australia. Thus, in the absence of research within the NOK tropical savanna, northern Australia provides a broader context from which patterns can be interpreted. This general introduction will present a broad overview of the northern Australian tropical savanna landscape, the NOK region and current knowledge of the small terrestrial mammal species. The aims and structure of this thesis are also presented.

1.2 Northern Australia

Northern Australia encompasses the northern regions of Western Australia, the Northern Territory and Queensland, but it is not distinguished by an administrative boundary. The commonly used delineation of northern Australia is that defined by the Tropical Savanna Cooperative Research Centre (Charles Darwin University, Northern Territory) based upon bioregions (TSCRC 2003; Interim Biogeographic Regionalisation for Australia (IBRA7) 2015) (Figure 1). Minor variations of this are sometimes used (Woinarski *et al.* 2007). Nevertheless, northern Australia generally excludes the Wet Tropics and Central Mackay Coast bioregions as they have a different climate, topography and environment from what is considered ‘true’ tropical savanna (Figure 1). This definition has been adopted in this study.

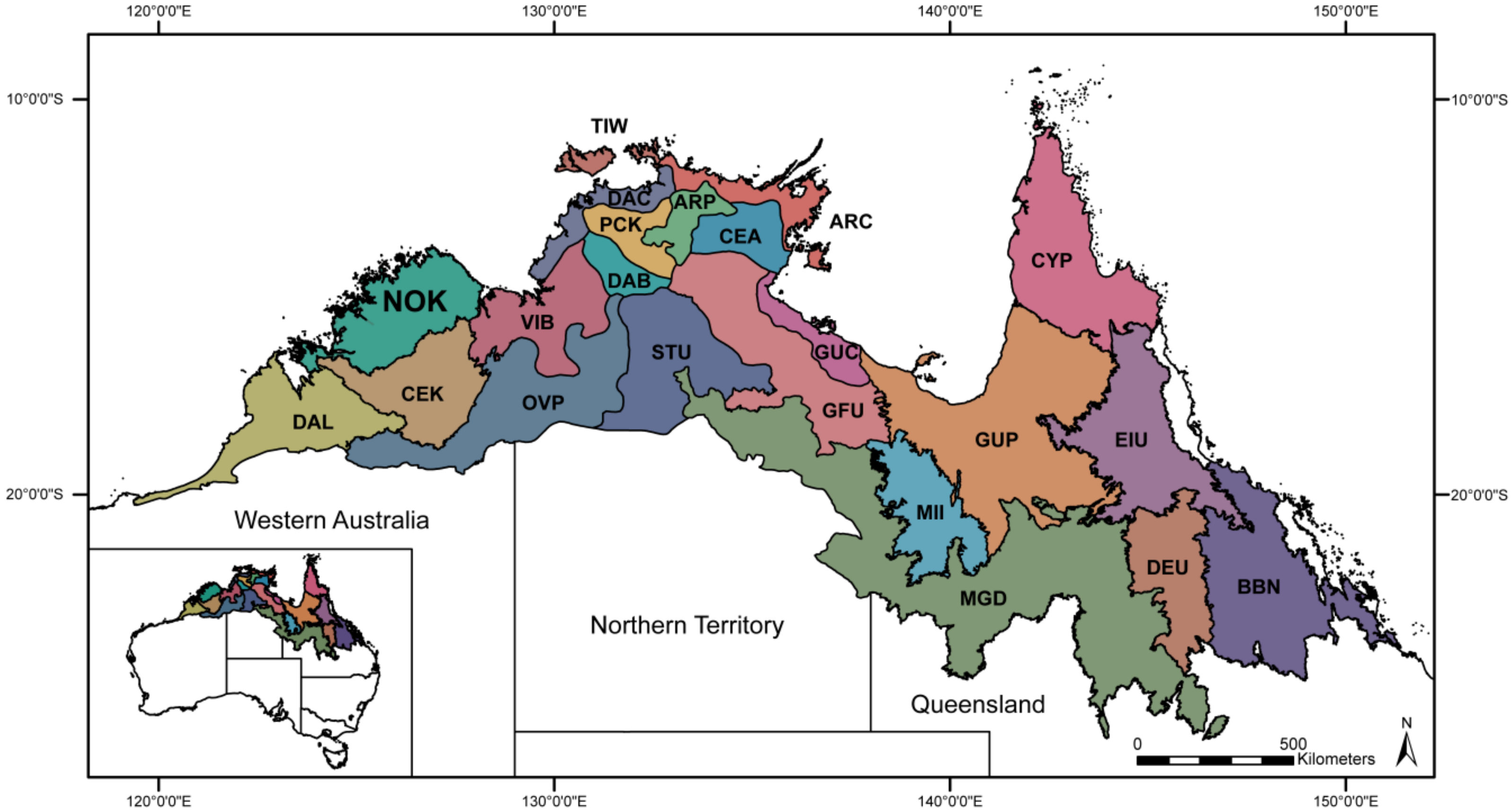

Figure 1. Bioregions classified as the northern Australian tropical savanna.

ARC: Arnhem Coast; ARP: Arnhem Plateau; BBN: Brigalow Belt North; CEA: Central Arnhem; CEK: Central Kimberley; CYP: Cape York Peninsula; DAB: Daly Basin; DAC: Darwin Coastal; DAL: Dampierland; DEU: Desert Uplands; EIU: Einasleigh Uplands; GFU: Gulf Fall and Uplands; GUC: Gulf Coastal; GUP: Gulf Plains; MGD: Mitchell Grass Downs; MII: Mount Isa Inlier; NOK: Northern Kimberley; OVP: Ord Victoria Plain; PCK: Pine Creek; STU: Sturt Plateau; TIW: Tiwi Cobourg and VIB: Victoria Bonaparte. Interim Biogeographic Regionalisation for Australia (IBRA7)(Interim Biogeographic Regionalisation for Australia (IBRA7) 2015).

The northern Australian tropical savanna comprises grassy landscapes with eucalypt woodlands and has a seasonally dry climate (Williams and Cook 2001a). Tropical savanna is globally recognised as a landscape consisting of scattered trees or woodlands with a grassy understorey, that experiences a 'dry' (predominantly rainless) season. These environments can be found in many regions including parts of Africa, South-East Asia, South America and India. The savanna of northern Australia is the largest tropical savanna globally remaining that is considered to be in good condition (Woinarski *et al.* 2007).

Northern Australia experiences two dominant seasons. The wet (or monsoon) season occurs from October/November to March/April. During the wet, temperatures and humidity are high, and there is high rainfall due to frequent thunderstorms formed in subtropical low pressure systems. For the remainder of the year, the 'dry' season, there is generally only light, sporadic, rainfall with lower temperatures and humidity. Average annual rainfall varies from >1600mm in the northernmost regions to 400-700mm further inland (Figure 2). Extreme weather events are a component of the climate, including severe tropical storms associated with the north-west monsoon. Throughout the year, average maximum temperature range from 25 degrees to 35 degrees Celsius (Bureau of Meteorology 2015b).

The high rainfall intensities have contributed to the deep weathering of the ancient landscapes in northern Australia. Precambrian basement rock gives rise to stable and deeply weathered landforms whilst Proterozoic sandstones form abrupt escarpments (Williams and Sofoulis 1967; Petheram *et al.* 2003). These ranges include stony, shallow skeletal soils and plateaus of deep sandy soils in the valley floors. Quaternary alluvials and pre-Tertiary fine sediments of basalts, limestone and mudstones generate more recent dynamic 'black soil plains' of cracking clays, alluvial flats and lateritic soils. It is the integration of the more rugged features of the landscape with the low topographic relief that has shaped the biodiversity of northern Australia (Woinarski *et al.* 2007). Cliffs and escarpments provide centres of endemism, particularly where these geographical features are concentrated. Conversely, the vast savanna plains promote the cohesive nature of the tropical savanna (Woinarski *et al.* 2007). Northern Australia's tropical savanna is dominated by eucalyptus forests with grassy understoreys (Figure 3). Variation in both substrate composition and water accessibility (rainfall, accumulation in low-lying areas and root access to groundwater) are the primary causes of different vegetation patterns (Woinarski *et al.* 2007; McKenzie *et al.* 2009).

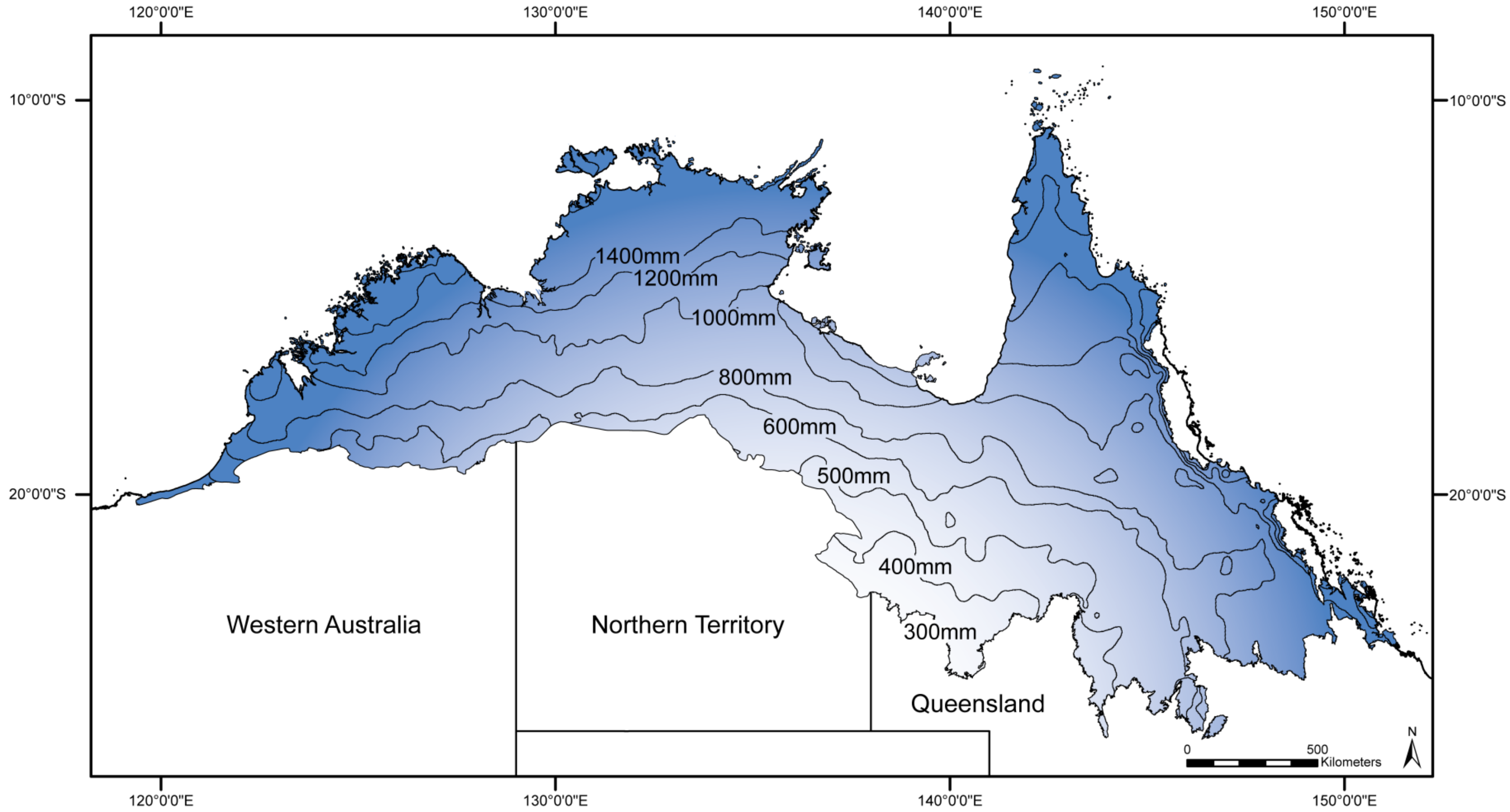

Figure 2. Average annual rainfall within northern Australia.

Modified from the Bureau of Meteorology (2015a)

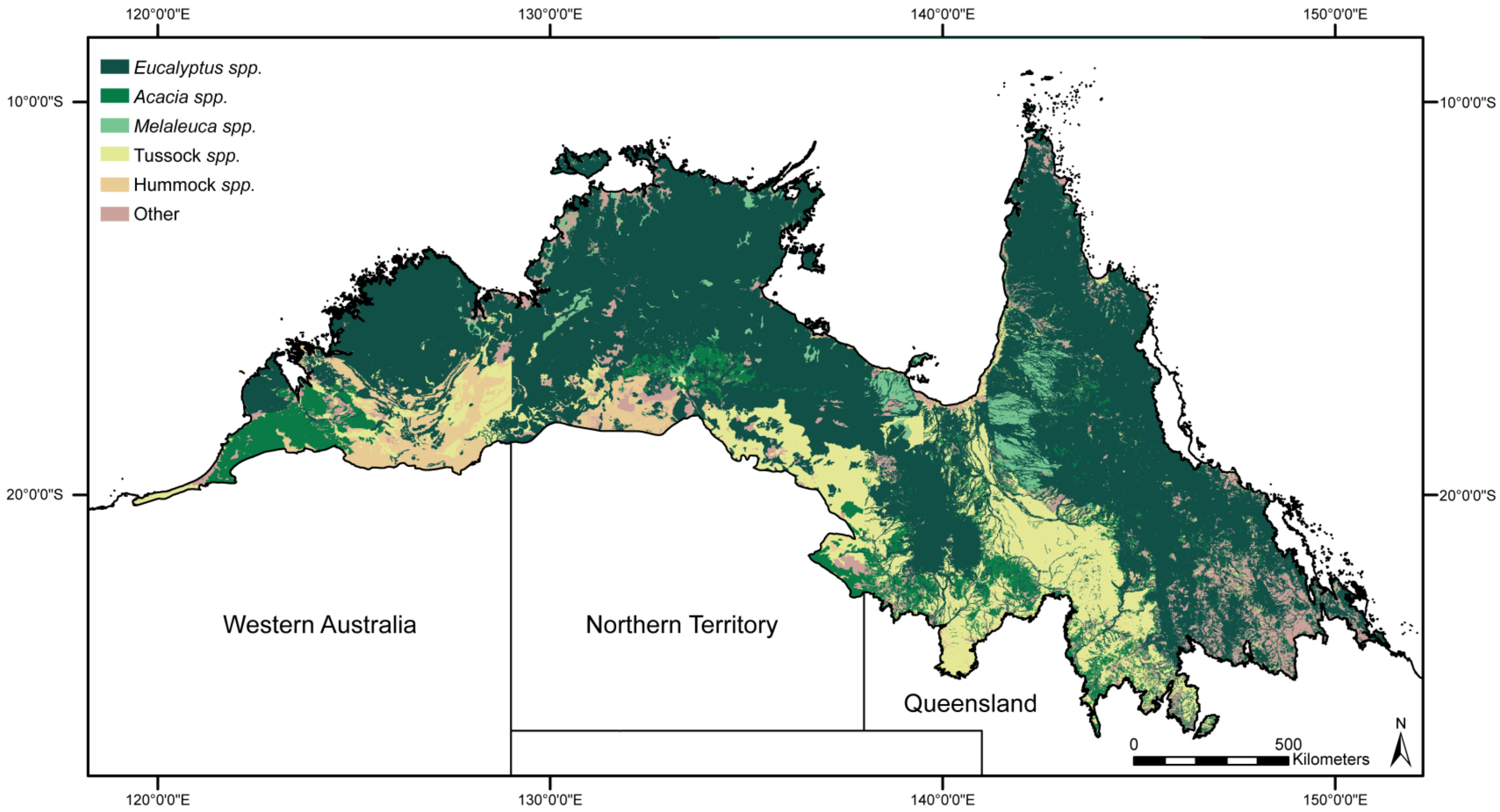

Figure 3. Dominant vegetation in northern Australia

Modified from the National Vegetation Information System (NVIS 2012).

Higher rainfall areas tend to be dominated by *Eucalyptus tetrodonta* and *E. miniata* open forests and woodlands . The semi-arid regions are dominated by shorter eucalypts with less cover (e.g. *E. tectifica* and *E. pruinosa*) and bloodwood species (e.g. *Corymbia terminalis*) in the northwest, and iron-barks, boxes (e.g. *E. crebra*, *E. melanophloia* and *E. brownii*) and bloodwoods (eg *C. erythrophloia*) in the northeast. Similarly, the tropical savanna's grassy understoreys vary with rainfall and soil composition. In the wetter areas, spear grasses (annual sorghums) are more common in the Northern Territory and Kimberley regions, whilst in the eastern Arnhem Land and Cape York Peninsula perennial sorghum (e.g. *Sarga plumosum*) and other tall grasses are dominant. In the semi-arid savannas, perennial grasses such as *Aristida* and *Chrysopogon* species predominate, whilst on skeletal soils in the driest areas, hummock grasses (*Triodia* spp.) are more common (Williams and Cook 2001b).

Other vegetation groups within northern Australia include Acacia dominated woodlands together with riverine and permanent swamp systems, typically dominated by Melaleuca and Pandanus species with sedge understoreys (Williams and Cook 2001b; Woinarski *et al.* 2007). Highly diverse and more specialised vegetation comprise monsoon vine forests, rainforests and thickets, and these are patchily distributed throughout northern Australia.

1.3 The Northern Kimberley (NOK)

1.3.1 *NOK Land use*

The NOK encompasses the northernmost part of western Australia (84, 201km ^{2}; Figure 1). It is one of the least populated regions in Australia (Taylor *et al.* 2006). The major land use and industry is pastoralism (beef cattle grazing) with pastoral properties operating in the region for more than a century, although, the cattle industry is not as extensive in the NOK as it is across northern Australia (Dray *et al.* 2010). This is predominantly due to the rugged landscape, large areas of poor grazing stony soils, and limited road access. Other major land tenures are conservation (national parks and conservation reserves), vacant Crown Land and Aboriginal Land (Figure 4). The NOK is of high indigenous importance (Roberts *et al.*, 1995). Other stakeholders with interests in the region include the scientific community, the mining industry, and the tourism industry, for both ecological and economical purposes (Russell-Smith *et al.* 2003b).

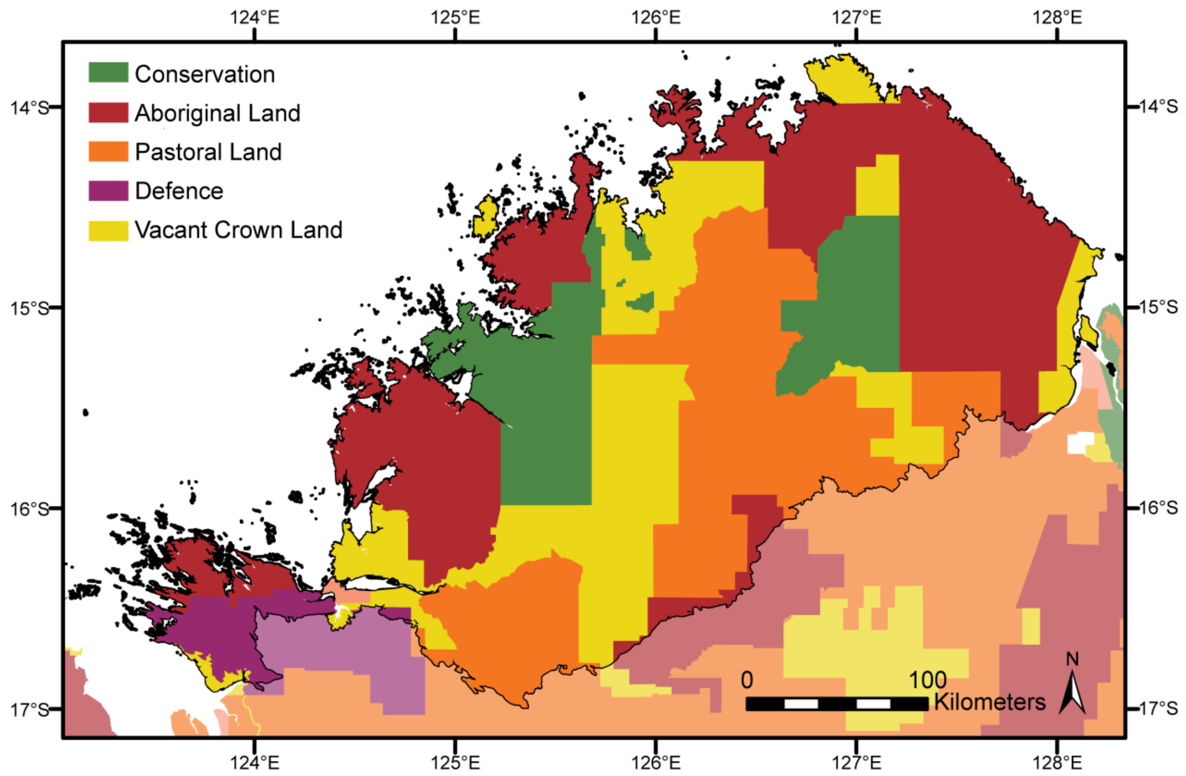

Figure 4. The major land uses within the Northern Kimberley.

Modified from Beston *et al.* (2001).

1.3.2 *NOK Subgregions*

The NOK is divided into two subregions – the western Mitchell (59, 709 km^2) and the eastern Berkeley (24, 492 km^2) (Figure 5) (Interim Biogeographic Regionalisation for Australia (IBRA7) 2015). Both subregions have climatic conditions typical of northern Australia, with hot tropical, subhumid weather and high summer rainfall (1000 – 1600mm annually). However, they vary in geological features and subsequently floristic composition. The Mitchell subregion is dominated by the highly dissected plateau of the Kimberley Basin, whilst the Berkeley subregion is less dissected with sandy soils mantling Pentecost sandstones (Graham 2001a; Graham 2001b). These two subregions similarly feature both Proterozoic siliceous sandstone with shallow sandy soils and Proterozoic volcanics mantled by red and yellow earths.

1.3.2.1 Vegetation

Vegetation of the two subregions comprises predominantly savanna woodland, although broad scale vegetation mapping indicates common and unique components whose extent varies within the subregions (Graham 2001a; Graham 2001b). *Eucalyptus teradonta* and *E. miniata* woodlands are common to both subregions. These include *E. miniata* and *E. tetrodonta* open-woodland over *Triodia bitextura* and *Sorghum* spp., and *E. miniata, E. tetrodonta* and variably *E. bleeseri* woodland over *Sorghum* spp.. The Mitchell subregion has a greater association with *E. tectifica* and *E. grandifolia* over *Sorghum* spp. and *Sehima nervosum* grasses. The Berkeley subregion features *Melaleuca* spp. and *Eucalyptus* spp. low woodland with *Triodia bitextura* hummock grasses. Both of the subregions have Melaleuca and Pandanus riparian forests along drainage lines but the Mitchell subregion has both more monsoon rainforest patches and more semi-deciduous vine thickets.

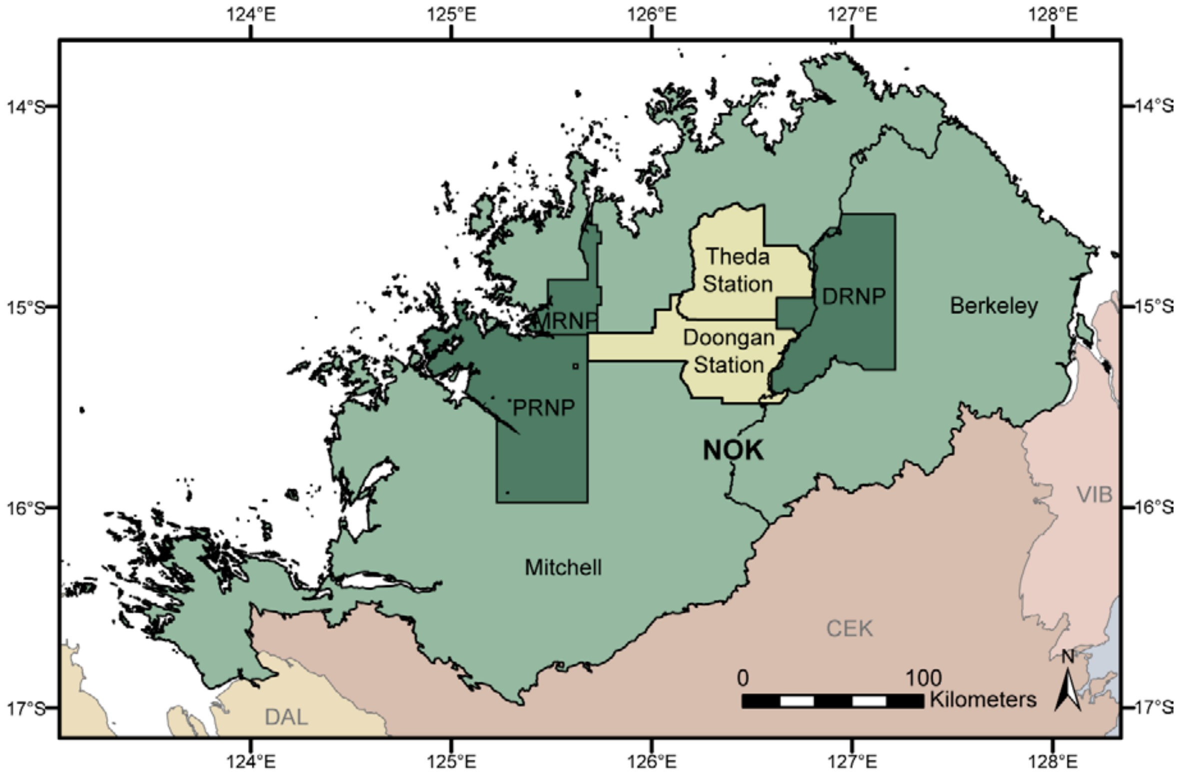

Figure 5. Northern Kimberley (NOK) bioregion with Mitchell and Berkeley subregions, national parks and Doongan and Theda Stations.

MRNP: Mitchell River National Park; PRNR: Prince Regent National Park and DRNP: Drysdale River National Park. Mitchell and Berkeley are sub regions identified in Interim Biogeographic Regionalisation for Australia (IBRA7) (2015).

1.4 Small mammals in the Northern Kimberley (NOK)

Small mammals were defined as those weighing <2kg and non-volant. This excludes larger species, such as most macropods, and volant species such as bats, which are not readily detected using standard trapping methods. Twenty-seven species of small mammals are currently known to occur in the NOK (Van Dyck and Strahan 2008). Most of the surveys of fauna in the NOK were conducted by the Department of Fisheries and Wildlife in Western Australia and the West Australian Museum, 20-30 years ago, within three national parks. This work comprised inventories of the northwestern Mitchell River National Park (MRNP) (Bradley *et al.* 1987), the western Prince Regent National Park (PRNP) (McKenzie *et al.* 1975a), and the eastern Drysdale River National Park (DRNP) (McKenzie *et al.* 1975b) (Figure 5). There has since been limited research in these national parks, or elsewhere in the NOK (Start *et al.* 2007; Radford 2012; Corey *et al.* 2013; Radford *et al.* 2014;). Nevertheless, recent observations have confirmed that all of the small mammal species known to occur in the region persist within at least one of the three major national parks (Start *et al.* 2007; Corey *et al.* 2013). There is little information on the status of the NOK fauna beyond these protected areas (Turpin 2015).

1.4.1.1 Muridae

The tropical short-tailed mouse, *Leggadina lakedownensis*, is the only *Leggadina* species that occurs in northern Australia. It has a continuous distribution throughout the Kimberley region and the central tropical region of the Northern Territory (Figure 6). These populations are discontinuous from populations in the northern parts of Cape York, Queensland (Figure 6) (Moro *et al.* 1998). There is little known regarding the ecology of this species and its current status in northern Australia is uncertain (Table 1).

There are three *Pseudomys* species that occur in the NOK. The central pebble-mound mouse, *Pseudomys johnsoni*, is widely distributed in the Kimberley, the Northern Territory, and Mount Isa (Queensland) regions of northern Australia (Kerle and Ford 2008). Until recently, *P. laborifex* was considered a separate species to *P. johnsoni* but genetic work has shown them to be paraphyletic and they are now considered as the single species *P. johnsoni*. The western chestnut mouse, *Pseudomys nanus*, is the largest of the *Pseudomys* rodents occurring in northern Australia. It is considered common in the tropical savanna regions of the Kimberley and Northern Territory (Robinson and Cooper 2008). The smallest of the *Pseudomys*, the delicate mouse, *Pseudomys delicatulus*, is widely distributed (Figure 6), although this is now considered to be a species complex (Breed and

Ford 2007) and research to determine species separation is ongoing (Bill Breed pers. comm.).

The grassland melomys, *Melomys burtoni,* is the only mosaic-tailed rat species that inhabits the NOK. In northern Australia, *M. burtoni* occurs in two disconnected areas, one extending from the NOK to the Top End of the Northern Territory and the other along coastal Queensland as far south as New South Wales (Figure 6) (Kerle 2008). Similarly, only one native *Rattus* species is known to occur in the NOK. *Rattus tunneyi* has a wide distribution that extends along the coastline of the southern Kimberley, to the Gulf of Carpentaria, and throughout the coastal areas in eastern Queensland (Figure 6) (Aplin *et al.* 2008).

Two tree rat species, *Mesembriomys* spp., occur in the NOK. The black-footed tree rat, *M. gouldii,* is considered to have separate populations in the northwestern Kimberley, Top End of the Northern Territory and far northeast Queensland. It is also present on the offshore Melville Island, Northern Territory (Figure 6) (Palmer *et al.* 2003). The golden-backed tree rat, *M. macrurus,* is restricted to the northwest of Western Australia, including a number of islands in the Buccaneer and Bonaparte Archipelagos. This species was more widely spread across the Top End, but has suffered major declines and it has not been found in the Northern Territory since 1969 (Woinarski 2000).

The brush-tailed rabbit rat, *Conilurus penicillatus*, is the only Conilurus species extant in Australia (*C. albipes* formerly inhabited southeastern Australia but has become extinct) (Van Dyck and Strahan 2008). *Conilurus penicillatus* is intermittently distributed in the coastal regions of the Kimberley as well as far-northwest of the Northern Territory (Figure 6). It is known from only ten locations in the NOK (Firth *et al.* 2010).

Two rock rat species occur in the NOK (Van Dyck and Strahan 2008). The common rock rat, *Zyzomys argurus,* is widely distributed and occurs in the Kimberley, Northern Territory and eastern Queensland (Figure 6). Conversely, the Kimberley rock rat, *Z. woodwardi,* is the largest species within this group and is endemic to the Kimberley region, where it also occurs on a number of offshore islands (Gibson and McKenzie 2012).

The water rat, *Hydromys chrysogaster,* is widely distributed throughout much of northern Australia, with its range extending down the east coast into the southwestern parts of South Australia (Figure 6). It is a semi-aquatic species and is considered common across its distribution (Speldewinde *et al.* 2013).

Table 1. Small mammal species known to occur in the Northern Kimberley and their conservation status.

Trends for Northern Australian Mammals from Fitzsimons *et al.* (2010), IUCN Status from IUCN (2015) and Conservation Status from Woinarski *et al.* (2014).

Species	Trends for Northern Australian Mammals	IUCN Status	Conservation Status
Muridae (Murinae)			
Leggadina lakedownensis	Uncertain	Least Concern	Least Concern
Pseudomys delicatulus	Stable	Least Concern	0
Pseudomys johnsoni	Uncertain	Least Concern	Least Concern
Pseudomys nanus	Some Decline	Least Concern	0
Conilurus penicillatus	Marked Decline	Near Threatened	Vulnerable
Mesembriomys gouldii	Marked Decline	Near Threatened	Endangered
Mesembriomys macrurus	Marked Decline	Least Concern	Near Threatened
Melomys burtoni	Stable	Least Concern	0
Rattus tunneyi	Marked Decline	Least Concern	Near Threatened
Zyzomys argurus	Stable	Least Concern	0
Zyzomys woodwardi	Uncertain	Least Concern	0
Hydromys chrysogaster	Stable	Least Concern	0
Dasyuridae			
Phascogale tapoatafa	Marked Decline	Vulnerable	Endangered
Pseudantechinus ningbing	Uncertain	Least Concern	0
Sminthopsis butleri	Some Decline	Vulnerable	Vulnerable
Sminthopsis macroura	Stable	Least Concern	0
Sminthopsis virginiae	Some Decline	Least Concern	0
Dasyurus hallucatus	Marked Decline	Endangered	Endangered
Planigale maculata	Stable	Least Concern	0
Peramelidae			
Isoodon auratus	Marked Decline	Vulnerable	Vulnerable
Isoodon macrourus	Some Decline	Least Concern	0
Macropodidae			
Petrogale burbidgei	Uncertain	Near Threatened	Near Threatened
Petrogale concinna	Some Decline	Data Deficient	Near Threatened
Pseudocheiridae			
Petropseudes dahli	Uncertain	Least Concern	0
Phalangeridae			
Trichosurus vulpecula	Marked Decline	Least Concern	Vulnerable
Wyulda squamicaudata	Stable	Data Deficient	Near Threatened
Petauridae			
Petaurus breviceps	Stable	Least Concern	0

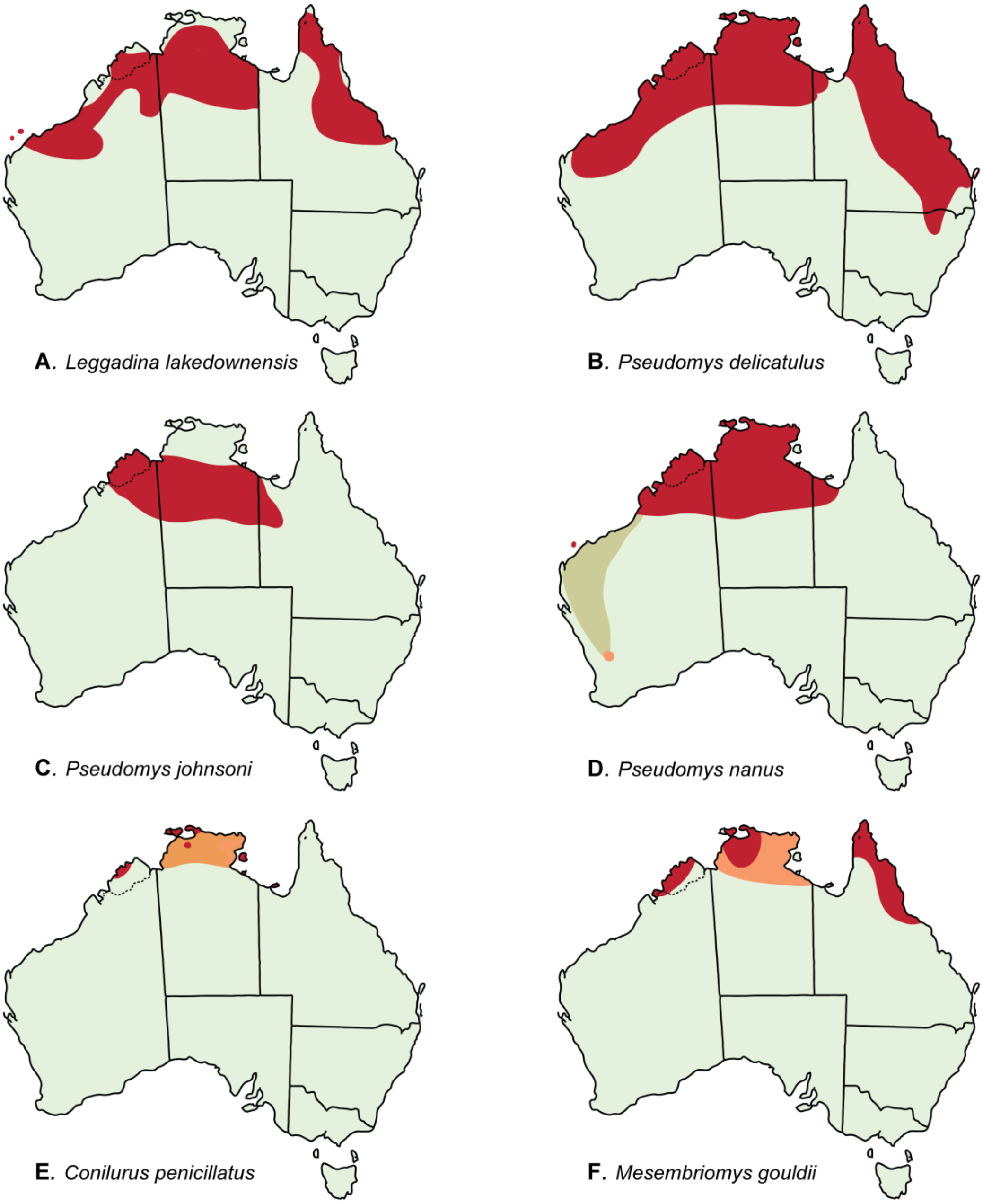

Figure 6. Distributions of the small mammal species known to occur in the Northern Kimberley.

Distributions shown for a) *Leggadina lakedownensis*, b) *Pseudomys delicatulus*, c) *Pseudomys johnsoni*, d) *Pseudomys nanus*, e) *Conilurus penicillatus*, f) *Mesembriomys gouldii*, g) *M. macrurus*, h) *Melomys burtoni*, i) *Rattus tunneyi*, j) *Zyzomys argurus*, k) *Z. woodwardi*, l) *Hydromys chrysogaster*, m) *Phascogale tapoatafa*, n) *Pseudantechinus ningbing*, o) *Sminthopsis butleri*, p) *Sminthopsis macroura*, q) *S. virginiae*, r) *Dasyurus hallucatus*, s) *Planigale maculata*, t) *Isoodon auratus* , u) *Isoodon macrourus*, v) *Petrogale burbidgei*, w) *Petrogale concinna*, x) *Petropseudes dahli*, y) *Trichosurus vulpecula*, z) *Wyulda squamicaudata* and aa)*Petaurus breviceps*. Modified from Van Dyck and Strahan 2008). Dashed line indicates Northern Kimberley bioregion.

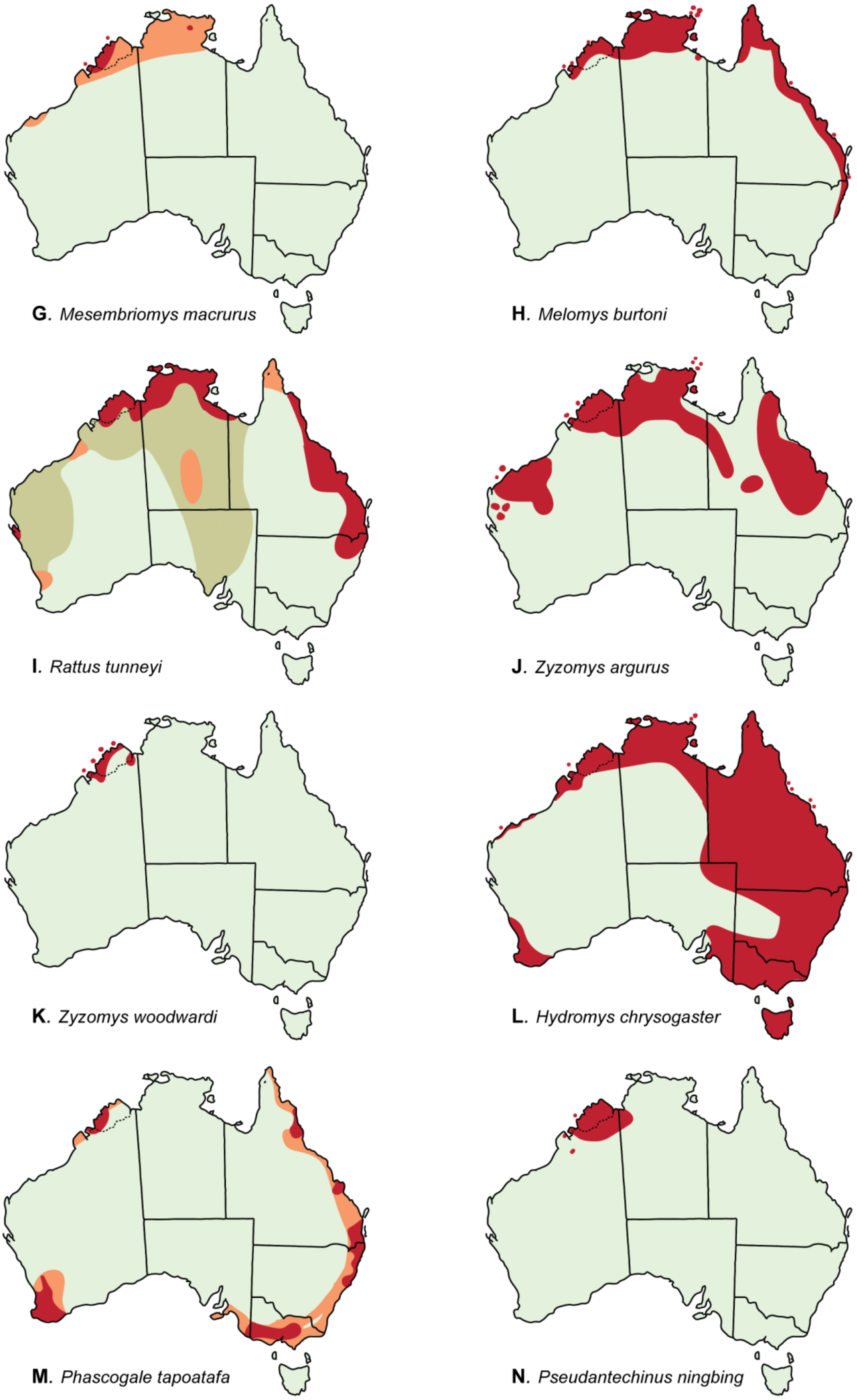

Figure 6. continued.

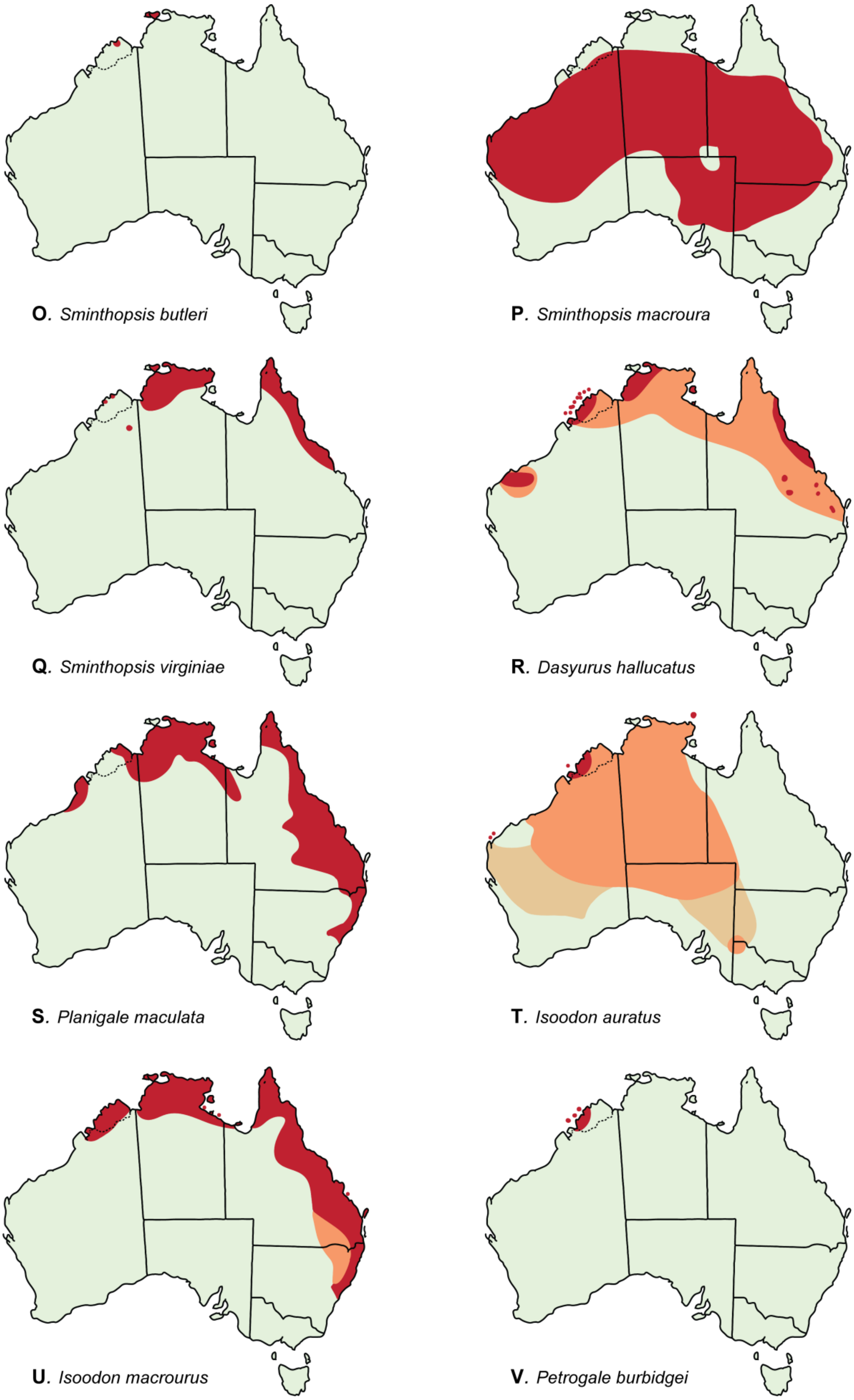

Figure 6. continued.

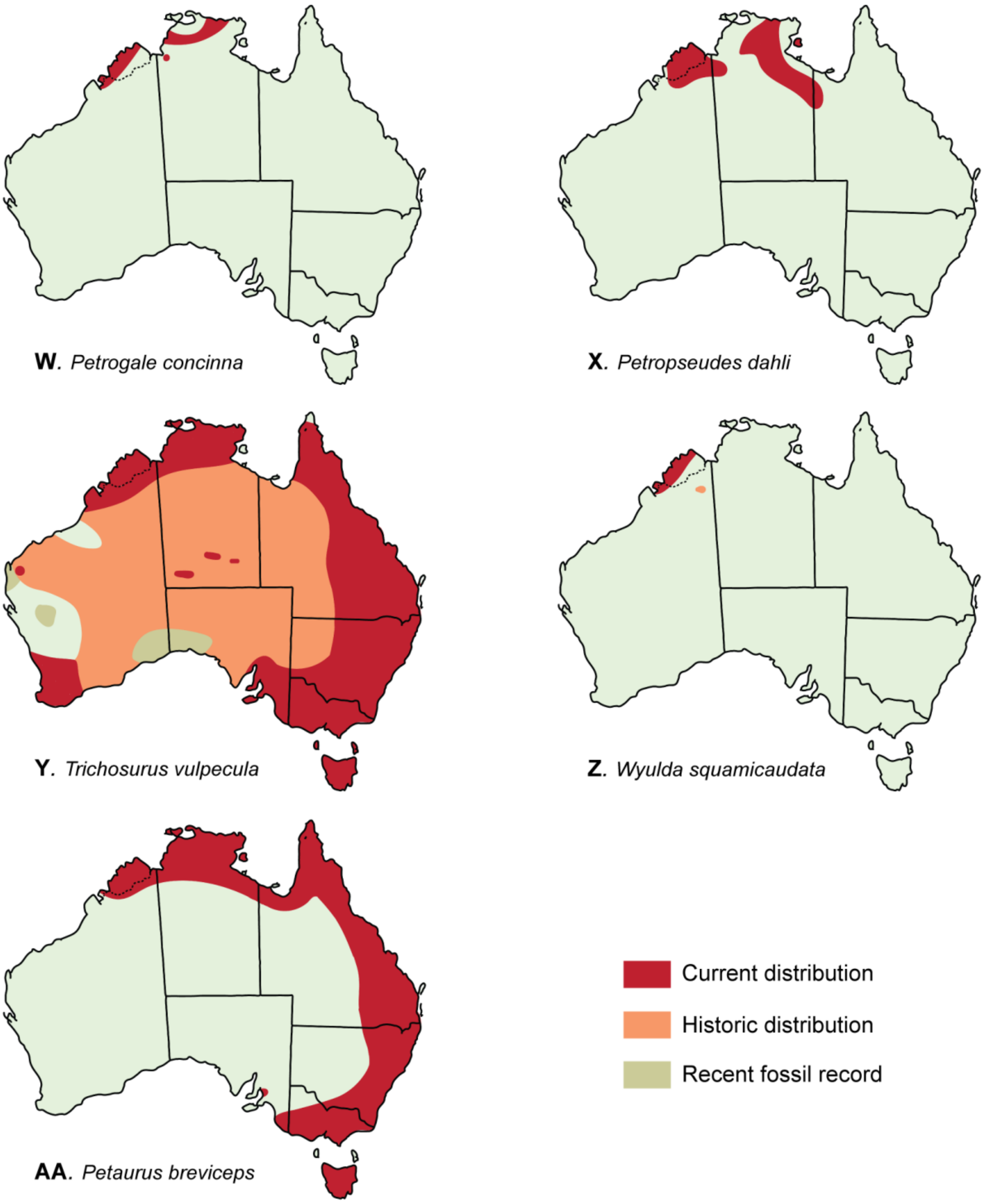

Figure 6. continued.

1.4.1.2 Dasyuridae

Two of the seven dasyurid species known to occur in the NOK are from the subfamily Dasyurinae. The largest of these is the northern quoll, *Dasyurus hallucatus*. It has severely contracted in range since European settlement (Braithwaite and Griffiths 1994). It is now limited to disjunct populations in the Kimberley, Top End and eastern Queensland in northern Australia (along with a population in the Pilbara, Western Australia) (Figure 6) (Hill and Ward 2010). Ningbing pseudantechinus, *Pseudantechinus ningbing*, primarily occurs in the Kimberley region, but extends into the western edge of the Northern Territory. It was first found in 1965 at Ningbing Station (Woolley 2008b).

The dasyurid subfamily Sminthopsinae includes three species that are known to occur in the NOK. This includes the red cheeked dunnart, *Sminthopsis virginiae,* which has three currently recognised forms (*S. v. nitela* in the Northern Territory and Western Australia, *S.v. virginiae* in Queensland and *S. v. rufigenis* in New Guinea) (Woolley 2008c). The stripe-faced dunnart, *S. macroura*, is widely distributed and occurs across central Australia and in the southern parts of northern Australia (Figure 6) (Morton and Dickman 2008). The other species is Butlers dunnart, *S. butleri*. It has a very limited distribution and has only been recorded within 20 kilometres of the northern Australian coast, on the Tiwi Islands of Northern Territory and at Kalumburu (NOK) (Figure 6) (Woolley 2008a).

Currently only one planigale species, the smallest of the marsupials, is known to occur in NOK. The common planigale, *Planigale maculata,* is distributed in the Kimberley, Northern Territory, Cape York Peninsula and the eastern Queensland coast (Figure 6 (Burnett 2008). Although not considered as occurring in the NOK currently, the long-tailed planigale, *P. ingrami,* is known to occur on the periphery of the NOK, and is also considered to be widely distributed across northern Australia but finer details are not clear. The *Planigale* genus is undergoing taxonomic revision with more species likely to be described in the near future (K. Armstrong pers. comm.).

Only one species of the highly arboreal phascogale, the brush-tailed phascogale, *Phascogale tapoatafa*, occurs in the NOK (Van Dyck and Strahan 2008). Two species of phascogale are currently recognised in northern Australia. Research into genetic and morphological variation indicates species separation of the Northern Territory population (northern brush-tailed phascogale, *Phascogale pirata*) from the population distributed in the Kimberley and Cape York (*P. tapoatafa*) (Woinarski *et al*. 2014). The nomenclature of *P*. *tapoatafa* will be used for the NOK species in the current study.

1.4.1.3 Peramelidae

Two peramelid species occur in northern Australia, the northern brown bandicoot (*Isoodon macrourus*) and the golden bandicoot (*Isoodon auratus*). The distribution of *I. macrourus* extends across northern Australia. This includes the northwestern Kimberley region, the northern parts of the Northern Territory and the eastern coast and northern tip of Queensland (Figure 6). Although there has been some range contraction for *I. macrourus* (it used to also occur in south-east Queensland and the Gulf of Carpentaria in the Northern Territory), it is still regarded as common in northern Australia (Woinarski *et al.* 2014). Conversely, the smaller of the two bandicoot species, *I. auratus*, was once widely distributed across half of the Australian continent but it has undergone marked decline (Table 1). It is now restricted to the northwestern Kimberley, four islands off the Western Australian coast and one island off the northeast Arnhem Land coast, Northern Territory (Figure 6) (McKenzie *et al.* 2008).

1.4.1.4 Macropodidae

Two species of small macropod are known to occur in the NOK. The monjon, *Petrogale burbidgei* is restricted to the northwest of the NOK region (Pearson *et al.* 2008). The narbalek, *Petrogale concinna,* also has a limited distribution and occurs only in the NOK and in the northern parts of Northern Territory (Figure 6) (Sanson and Churchill 2008). There has been marked recent decline in abundance and range of *P. concinna* in northern Australia, including in the north Kimberley (Woinarski *et al.* 2014).

1.4.1.5 Pseudocheiridae

The rock-ringtail possum, *Petropseudes dahli,* is restricted to rocky escarpments in northern Australia (Webb *et al.* 2008). It is known to occur from the NOK through Arnhem Land and the Gulf of Carpentaria in the Northern Territory, to western Queensland (Figure 6). *P. dahli* populations are considered to be locally common across its range (Webb *et al.* 2008).

1.4.1.6 Phalangeridae

The common brush-tailed possum, *Trichosurus vulpecula,* and the scaly-tailed possum, *Wyulda squamicaudata,* both occur in the NOK. *Trichosurus vulpecula* historically occurred across most of Australia but has suffered some range contraction (Figure 6). The taxonomy of *T. vulpecula* is not fully resolved, and the northwest population in western

Australia and the Northern Territory has recently been considered as *T. v. arnhemensis* (Woinarski *et al.* 2014). Nevertheless, there has been marked recent decline in abundance and range *T. vulpecula* in northern Australia, including in the north Kimberley (Woinarski *et al.* 2014). *Wyulda squamicaudata* was thought to be restricted to the NOK, however recent rediscovery has indicated that it still occurs in the east Kimberley, where it originally was thought to have become locally extinct or to be a historically erroneous record (Figure 6) (Doody *et al.* 2012).

1.4.1.7 Petauridae

The sugar glider, *Petaurus breviceps*, is the only glider species known to occur in the NOK. It has a wide distribution and is considered to be relatively common but occurs at low densities in northern Australia (Figure 6) (Suckling 2008).

1.5 Changing status of small mammals in northern Australia

The NOK is one of the few bioregions in Australia where no mammal species is known to have become extinct since European settlement. Studies of the status of Australia's terrestrial mammals have shown that the NOK is one of only nine of the 85 bioregions in Australia to have retained its entire mammalian fauna, with the other eight all also in northern Australia (McKenzie *et al.* 2007; Burbidge *et al.* 2008). Remarkably, only two bioregions (NOK and Tiwi Coburg) have all of their mammalian fauna considered to persist in >50% of their former range, with the other 83 Australian bioregions having at least one species with <50% persistence. This highlights the importance of the NOK for conserving the remaining fauna. However, there is increasing evidence that suggests the mammal fauna of northern Australia, including the NOK, can no longer be assumed to be secure (Woinarski *et al.* 2001). It has been found that two thirds of the small mammal species occurring in northern Australia show some evidence of a reduction in abundance and/or distribution (Fitzsimons *et al.* 2010).

Whilst there is little information on the abundance and distribution of small mammals in the NOK, a number of studies in northern Australia provide evidence for localised changes in small mammal populations. Kakadu National Park (Northern Territory) has been studied comprehensively, including long-term monitoring of the small mammal species. Braithwaite and Muller (1997) reported short term declines (1986-1993) in overall abundance of several mammal species and dramatic declines in *Antechinus bellus*, *R. tunneyi* and *P. delicatulus*, debatably attributed to reduced availability of groundwater. Resampling of these sites in 1999 showed further decline in six small mammal species. These included three rodents (*R. tunneyi*, *M. gouldii* and *Rattus colletti*), two dasyurids (*A. bellus* and *D. hallucatus*) and a bandicoot species (*Isoodon macrourus*)(Woinarski *et al.* 2001). Contrastingly, increases in abundance were shown in four species (*P. delicatulus, P. nanus*, *M. burtoni* and *S. virginiae*), which was attributed to these species being disturbance-favoured generalists. However, resampling in 2001-2004 and again in 2007-2009 (Woinarski *et al.* 2010) documented further severe decline in the small mammal fauna, most markedly in *D. hallucatus*, *A. bellus*, *I .macrourus* and *R. tunneyi*. These authors attributed declines to no single impacting factor, but to broad-scale, interactive environmental change associated with modifications in land management due to the abolition of traditional Aboriginal land practices.

Anthropogenic driven changes in small mammal fauna have also been found in the southwest of the Kimberley (McKenzie 1981). Recent accounts and literature, along with subfossil and museum records, showed that five small mammal species have become regionally extinct since European settlement in the 1890's (*R. tunneyi*, *M. macrurus, P. tapoatafa*, *Bettongia lesueur* and *I. auratus*). There have been similar findings on the Sir Edward Pellew islands (Northern Territory) with *R. tunneyi*, *M. gouldii*, *M. macrurus*, *I. auratus, I. macrourus* and *D. hallucatus* considered to have markedly declined or become regionally extinct in the last 50 years (Woinarski *et al.* 2011b).

It is likely that decline in small mammals in northern Australia is due to the combination of many influences and it is presumed that ecosystem processes and management issues are similar across the region. Changing burning patterns and cattle grazing are thought to be significant drivers of landscape modification. Additionally, the presence of introduced species, especially feral cats (*Felis catus*) and cane toads (*Rhinella marina*), may have contributed to the drastic declines in mammal fauna. Whilst there is little information specific to the NOK, the effects of fire regimes and burning patterns, cattle, as well as other introduced species, are considered to be similar in the NOK to elsewhere in northern Australia. These are discussed further below.

1.5.1 Rainfall

Hydroecology is thought to be a major driver of change in northern Australia (Woinarski *et al.* 2007). There is torrential rain and flooding during the wet season in the NOK. This is contrasted with the dry season, where there is a water deficit, and potential evaporation greatly exceeds rainfall. Rainfall in the NOK, and across northern Australia, is largely responsible for the dynamic nature of the landscape. The amount of rainfall during both the wet and the dry seasons varies annually in the NOK (Shi *et al.* 2008). Variation in rainfall can cause changes in vegetation by both promoting growth and density in periods of good rain and causing die back during periods of below-average rainfall (Woinarski *et al.* 2007; Fensham and Holman 1999). Furthermore, the influence of rainfall variation may be different across different land forms, such as in riparian areas (Braithwaite and Muller 1997).

There is a rainfall gradient in the NOK, whereby the northwest tends to receive higher rainfall than the southeast (Bureau of Meteorology 2015a). This rainfall gradient is thought to influence the presence and abundance of small terrestrial mammals (Start *et al.* 2012b). However, the relationships and precise mechanisms associated with rainfall generated change are not well understood for the NOK, nor for northern Australia (Radford *et al.* 2014).

1.5.2 *Fire*

The northern Australian landscape has been shaped by both natural and anthropogenic fire (Dyer *et al.* 2001). Tropical Australia has the highest annual frequency of lightning strikes in Australia. In recent history, low intensity, small scale fires were used in traditional Aboriginal burning practices. These created a mosaic effect of patchy burns and vegetation of variable age. However, fire regimes have changed dramatically due to European influence, with a propensity for hot, intensive, broad-scale, late-dry season fires (Russell-Smith *et al.* 2003a).

Studies of fire in northern Australia have indicated that both the frequency and the intensity of fire affect the ecological responses to burning. Fine-scale habitat patchiness, resource diversity and structural diversity are reduced with frequently and intensely burnt landscapes. Fire-sensitive species such as obligate seeders *Callitris intratropica* (Bowman and Panton 1993) and *Acacia shirleyi* (Woinarski and Fisher 1995), and habitats such as small rainforest patches (McKenzie and Belbin 1991) and sandstone heaths (Russell-Smith *et al.* 2002) are deleteriously affected by frequent, hot burns. Conversely, infrequently burnt savanna has been associated with woody thickening and the loss of herbaceous landscapes (Bastin *et al.* 2003; Vigilante and Bowman 2004a).

Fire has been shown to affect the abundance of small mammals, with species specific responses both immediately following fire and temporally with burning patterns. In the Central Kimberley, surveys of similar habitats in unburnt and burnt sites five weeks after a >7000km^2 extensive fire showed that immediate responses of small mammals were species specific (Legge *et al.* 2008). For instance, *P. delicatulus* showed little variation in burnt compared to unburnt sites, whilst *R. tunneyi* and *P. nanus* were more abundant in unburnt sites. However, the short-term and more temporal patterns differ, with other studies showing contradictory results with repeated measures over a greater period of time, such as the increase in abundance of *Rattus tunneyi* with frequent burns (Price *et al.* 2005).

The temporal impacts of fire regimes have been shown to negatively affect survival of *I. macrourus* populations, which were studied under different fire treatments at Kapalga (Kakadu National Park, Northern Territory) (Pardon *et al.* 2003). During five years of experimentation, *I. macrourus* had essentially been eliminated over a 300km^2 area as a result of both direct mortality and emigration. However, unburnt sites also reflected this decline, and it has been suspected that the floristic homogeneity found in unburnt sites is also unfavorable for this species. A similar scenario was depicted for *C. penicillatus* with decline in both unburnt sites and sites with late-dry season fires (Firth *et al.* 2010).

A recent study in the NOK has shown that abundance and richness is influenced by the frequency of fire, particularly fires that occur late in the dry season (Radford *et al.* 2015). Later dry season fires tend to be both more extensive and more intense. These inordinate burns leave limited habitat, such as ground cover, to remain. The spatial extent of fire was also found to be important for small mammals, whereby the larger the fire extent, the further the potential recolonizing populations need to travel (Radford *et al.* 2015). Although fire is thought to be one of the key drivers in the NOK, there is limited understanding of its role and influence.

1.5.3 Grazing

Feral or wild domestic cattle (*Bos taurus* or *B. indicus*) are found in the pastoral areas of northern Australia and have spread to establish free-roaming populations. The impacts of pastoralism on vegetation have been relatively well documented (Gardener *et al.* 1990; Scanlan *et al.* 1996; Ash and Corfield 1998; Ash and McIvor 1998; McIvor 1998). Cattle negatively impact native vegetation communities through grazing, browsing and trampling (Long 2003). Cattle herd congregations and the effect of ungulate hoofs (an element unfamiliar to the Australian landscape until European settlement) cause changes in the upper soil layers and can increase the occurrence of erosion (Woinarski and Fisher 2003).

Although, there has been limited research on the impacts of pastoralism on fauna (Woinarski 1999), it has been recognised to be at least partly responsible for broad-scale changes in biodiversity (Woinarski and Ash 2002). Recently, a study by Legge *et al.* (2011a) showed increases in both the abundance and richness of small mammals across three years following cattle removal on Mornington Station in the Central Kimberley. Three species of small native rodents (*L. lakedownensis*, *P. nanus* and *R. tunneyi*) responded positively to the cattle removal, whilst *I. macrourus* showed little response. Legge *et al.* (2011a) found that the greatest increase in small mammal abundance was in the third year after cattle removal, and suggested that this may be due to changes in the ground cover, namely increased food availability and increased protection from predation.

It has been suggested that feral herbivores are not as abundant in the NOK as they are in northern Australia as a whole, and it has been proposed that the lack of faunal extinctions in the NOK may be due to the lower densities of cattle (Burbidge and McKenzie 1989). However, there is great paucity in the understanding of the role of cattle in causing environmental change in northern Australia.

1.5.4 Effects of introduced species

1.5.4.1 Feral Cats

Feral cats (*Felis catus*) became established in Australia by the 1850’s from both unplanned and intentional releases and cats are now distributed throughout the northern tropical savanna (Abbott 2002, 2008; Abbott *et al.* 2014; Dickman 1996b;). Feral cats are carnivorous and depredate small mammals, birds, reptiles, amphibians, fish and insects

(Burbidge and McKenzie 1989). They also carry infectious diseases such as toxoplasmosis and sarcosporidosis which are parasitic diseases transmissible to native mammals. Infection with these diseases often causes mortality in native Australian species (Clarke *et al.* 2000). However, the extent to which pathogens have contributed to native species' decline remains unknown (Dickman 1996b).

Feral cats are a significant predator of small native mammals in Australia. The role of cats in mammal declines has been demonstrated by both the hindrance of release programs (Gibson *et al.* 1994; Christensen and Burrows 1995; Friend and Thomas 1995) and the persistence of native species' in cat-free populations (Burbidge 1999). The impact of feral cats on small mammals in northern Australia has been inferred from island populations where localized extinctions have coincided with the presence of cats, and conversely, where species have persisted on islands that are cat-free. The regional extinction of *C. penicillatus*, *D. hallucatus*, *P. tapoatafa* and *Rattus sordidus* from the Sir Edward Pellew group of islands (Northern Territory) coincided with 20 – 30 years since the release of cats (Woinarski *et al.* 2011b). Correspondingly, *I. auratus* and *C. penicillatus* provide notable examples of small mammal species that have severely declined on mainland Australia, but persist on cat-free islands (Southgate *et al.* 1996; Firth *et al.* 2010). Recently, feral cats in the Central Kimberley were found to occur at low density and have large home ranges, but thought to be nevertheless having a significant impact on the small mammal fauna (McGregor *et al.* 2015). Beyond this, basic information on cat density, ecology and the impact they are having in northern Australia is severely lacking.

1.5.4.2 Cane toads

The cane toad (*Rhinella marina*) was introduced to Queensland in 1935 to control the cane beetle (*Dermolepida albohirtum*) in sugar cane, however, it has proved to be a highly invasive pest (Sutherst *et al.* 1995). Cane toad distribution has spread both north and west from the initial introduction site with toads now being found throughout Queensland and the Northern Territory. They have invaded the eastern edge of the Kimberley region of Western Australia (Taylor and Edwards 2005) and were predicted to colonise the entire mainland of the Kimberley by 2015 (Fitzsimons *et al.* 2010). So far, they have been detected as a far as west as DRNP (DPAW 2015a).

Cane toads adversely affect native species as predators, competitors and as a prey items (Shine 2010). Cane toads prey upon native species that are small enough to be consumed, including insects, frogs and small reptiles, mammals and birds. The toads can reach extremely high densities and compete with native species for both food and shelter. Furthermore, their toxicity has also been shown to cause mortality in native Australian species (Burnett 1997; O'Donnell 2009). Most toxic anuran species are poisonous in only one of their life stages, but ingestion of the cane toad toxin, regardless of whether from the egg, tadpole, juvenile or adult life-cycle stage, is fatal for most animals.

The decline of native mammals in northern Australia appears to have preceded the arrival of the cane toads, making the effects of their invasions hard to decipher (Catling *et al.* 1999). More research into the impacts of cane toads is needed to fully comprehend their impact, including the potential of ancillary effects on ecological communities such as the release of pressure by reduced abundance (mortality) of native predators and the increased resource competition pressures from high densities of toads (Shine 2010). This study of Doongan and Theda Station provides baseline information prior to the impending arrival of the cane toad.

1.6 Thesis aims

The aim of the research presented in this thesis was to examine the small mammal fauna of two pastoral stations, Doongan and Theda Stations, in the NOK bioregion. This is the first time the small mammal fauna has been surveyed on these stations. As such, this study provides novel records of the occurrence of small mammal species in the NOK.

Whilst it is recognised that these properties are currently under the same tenure, and similar land management practices, they are considered as separate entities. As such, this thesis has been structured to describe all of the small mammal records obtained during this study. Whilst the aim of this thesis is to describe the small mammal fauna, the environments on the stations have similarly not been surveyed previously. Environmental assessments and subsequently broad categorisation of the different habitats that occur on the stations were undertaken. This is the first time these have been described for either station, with the descriptions detailed within Chapter 2 and Chapter 3. Throughout this study, the findings on Doongan and Theda Stations are compared to the three adjoining national parks, but given the literature for the NOK is sparse, context for findings is also drawn from the broader northern Australia.

1.6.1 *Synopsis and general aims of chapters*

Chapter 2 describes the small mammals recorded on Doongan Station. This chapter details the locations where surveys were undertaken, identifies different habitat types and describes the survey effort on Doongan Station. The species detected on Doongan Station are summarised, along with the broad habitats in which they were detected. Comparison of Doongan Station is limited by the lack of comparable data in the NOK, hence the species recorded are qualitatively compared to those known to occur on the adjacent national parks and in the NOK bioregion.

Chapter 3 describes the small mammals recorded on Theda Station. This chapter details the survey locations, habitat types and survey effort on this Station. The species detected on Theda Station are summarised, along with the broad habitats in which they were detected. The findings in Chapter 2, on Doongan Station, are compared to the records for Theda Station. Comparisons of the two stations examine species presence and abundance, including total and yearly records, and species' presence in the different broad habitats. Chapter 3 establishes similarities and differences between the species records and their trends. Qualitative comparisons are made between changes in yearly trap success and possible causes of these changes, such as rainfall, fire and cattle presence.

Chapter 4 uses a subset of the pooled data described in Chapters 2 and 3 to investigate the effects of broad-scale factors on the small mammal community. A relatively new modelling technique, using a multiple regression and multivariate framework, is used to compare the relative abundance of species. Environmental factors investigated include time since fire and fire frequency, seasonal rainfall and rainfall gradient, along with land system and the type of surface rock. The potential role of these in driving changes within the small mammal community is discussed.

Chapter 5 summarises the finding in Chapters 2, 3 and 4. The presence and relative abundance of the species found to occur on Doongan and Theda Stations are discussed. The potential reasons for absence of each of the species that were not detected on the stations, but known to occur in the NOK, are discussed. The relationships and associations of environmental variables with each species are raised throughout. Additional detail is discussed regarding of the influence of broad-scale environmental variables on the small mammal community.

1.7 Thesis structure

Each chapter of this thesis is written as a separate entity for publication in different journals. These papers have been written with multiple authors and as such occasionally include reference to ‘our research’. The contribution and declaration of authors are indicated at the beginning of each chapter. There is some minor duplication of background introduction material, study area, methods, and study species, as is required for establishing context in stand-alone articles. Text formatting and numbering of figures and tables have been modified for consistency throughout this thesis. However, all other content reflects that of the published or submitted articles.

1.8 Ethics and permits

Surveys were funded by Dunkeld Pastoral Co Pty Ltd, with assistance in some years by the Department of Parks and Wildlife (Western Australia, previously Department of Conservation and Environment, 2012) and Jobs Fund (Commonwealth of Australia, 2010 & 2011). Work was carried out with University of Adelaide Ethics Committee permits (S-003-2008, S-2012-086) and Department of Environment and Conservation permits (Regulation 17: SF005918, SF006508, SF007102, SF007650, SF008365, SF008987 & SF009599).

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Chapter 2
Small terrestrial mammals on Doongan Station in the Northern Kimberley, Western Australia

Grassland Melomys
Melomys burtoni

Small terrestrial mammals on Doongan Station in the Northern Kimberley, Western Australia

Liberty G.M. Olds[A], Cecilia Myers[B], Jim Reside[C], George Madani[D], Alexander Dudley[E], Sally Potter[F], Raz Martin[G], Ernie Boona[H], Tamara Waina[H], David A. Taggart[A]

[A] School of Biological Sciences, University of Adelaide, Adelaide, SA, 5000, Australia

[B] Dunkeld Pastoral Company Pty Ltd, Dunkeld, Vic, 3294, Australia

[C] Wildlife Unlimited, Bairnsdale, Vic, 3875, Australia

[D] Wildlife Consultant, chiro_ptera@hotmail.com

[E] Wildlife Consultant, ap_dudley@yahoo.com.au

[F] Research School of Biology, The Australian National University, Acton, ACT, 2601, Australia

[G] Wildlife Consultant, raz.martin@skymesh.com.au

[H] Kalumburu Remote Community, Kalumburu, WA, 6740

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2.1 Statement of Authorship

By signing the Statement of Authorship, each author certifies that their stated contribution to the publication is accurate and that permission is granted for the publication to be included in the candidate's thesis.

Liberty Olds: (Candidate)__________________________ Date:__________________

Small mammal trapping, data collection, habitat assessments, data analysis, preparation of the full manuscript including all Tables and Figures, and acted as the corresponding author.

Cecilia Myers:_ Date: 17/4/16

Provided on-ground expertise, land management, field support and data collection.

Jim Reside: Date: 13/04/16

Provided field support and data collection.

George Madani: Date: 12/4/16

Provided field support and data collection.

Alexander Dudley: Alexander Dudley Digitally signed by Alexander Dudley DN: cn=Alexander Dudley, o=Alexander Dudley, ou=Sole Trader, email=ap_dudley@yahoo.com.au, c=AU Date: 2016.04.20 01:00:07 +10'00' Date: 19/4/2016

Provided field support and data collection.

Sally Potter: _ Date: 12·04·16

Provided field support and data collection.

Raz Martin: . Date: 26/4/2016.

Provided field support and data collection. Signed by David Taggart on behalf of Raz Martin.

Ernie Boona: _ Date: 26/4/2016

Provided field support and data collection. Signed by David Taggart on behalf of Ernie Boona.

Tamara Waina: _ Date: 26/4/2016

Provided field support and data collection. Signed by David Taggart on behalf of Tamara Waina.

David Taggart: _ Date: 26/4/2016.

Provided field support, data collection and manuscript revision.

2.2 Abstract

There are significant gaps in the knowledge of the small terrestrial mammals (<2 kg) in the Northern Kimberley bioregion (NOK). There have been no known extinctions of small mammals in the NOK, despite broad-scale declines being observed across much of northern Australia. The few studies in the NOK have focused largely on three major national parks and NOK islands and thus may not be fully representative of the region. Mammal surveys were undertaken on Doongan Station, a pastoral property adjacent to these national parks to determine the presence/absence of small mammals. Five species were found to be common (*Pseudomys nanus*, *P. delicatulus*, *Rattus tunneyi*, *Zyzomys argurus* and *Sminthopsis virginiae*), two species were detected less frequently (*Leggadina lakedownensis* and *Isoodon macrourus*), and four species were scarcely detected (*Melomys burtoni*, *Hydromys chrysogaster*, *Planigale maculata* and *Dasyurus hallucatus*). Two species were detected only opportunistically outside of the survey effort (*Petropseudes dahli* and *Petaurus breviceps*). The trap success was consistently low, with levels in most years being below those regarded as critically low elsewhere in northern Australia.

2.3 Introduction

The small mammalian fauna of northern Australia is considered to be in rapid and ongoing decline (Woinarski *et al.* 2011a). A decline in both the richness and abundance of many small to medium-sized native mammals has been observed over the last 20 years in Kakadu National Park, which provides the most extensive, long-term monitoring of mammals in northern Australia. This pattern was first observed between 1986 and 1993 and was initially reported to be the result of low rainfall (Braithwaite and Muller 1997). Resampling after good rainfall seasons in 1999, however, revealed that the declines were sustained or had worsened (Woinarski *et al.* 2001). Evidence has since shown this trend is continuing, with the number of individuals declining by 75% when comparing plots from 2007-2009 with those from 2001-2004 (Woinarski *et al.* 2010).

The Northern Kimberley (NOK) is one of the last bioregions in Australia to have no known extinctions within its mammalian fauna. The terrestrial mammal assemblage of the NOK is similar to that observed in the Top End of the Northern Territory (Burbidge *et al.* 2008), suggesting that the NOK fauna may also be vulnerable to threats and subsequent declines. Despite this, there are significant gaps in knowledge of the distribution and status of the species in this region (McKenzie *et al.* 2009). This is most apparent for the privately leased land in the NOK, for which little or no information has been recorded on the status of small terrestrial mammals (defined in this study as non-volant species weighing <2 kg).

Surveys on three national parks in the NOK provide the most extensive information regarding small mammals in this region. These reserves are geologically similar (Speck *et al.* 1960), however their physiography varies. Mitchell River National Park (MRNP; 1153 km^2) comprises basalt slopes and hilly volcanic country, laterite-capped mesa and rugged sandstone plains and gorges (Wilson 1981). Prince Regent National Park (PRNP; 6338 km^2) predominantly comprises rugged sandstone boulder country of hills, ranges and plateaux and less volcanic country than MRNP with fewer rocky outcrops and basalt boulder screes (Miles *et al.* 1975). Drysdale River National Park (DRNP; 4482 km^2) is on the eastern border of the NOK and is less dissected than the other reserves, with more gently undulating sandstone plains and uplands (Kabay *et al.* 1975; see Figure 7 for localities). Comprehensive biological surveys of these national parks were conducted 20-30 years ago (McKenzie *et al.* 1975a; McKenzie *et al.* 1975b; Kitchener *et al.* 1981; Bradley *et al.* 1987). Only a limited number of studies have since been undertaken in the NOK, primarily revisiting some of the previously surveyed sites (Start *et al.* 2007; Corey *et al.* 2013). These studies, along with records from hiking expeditions (Turpin 2015), provide the most recent accounts of mammals in the NOK. Other research has focused on Kimberley rainforests (Friend *et al.* 1991), NOK islands (Gibson and McKenzie 2012), and burning patterns and vegetation responses (Fisher *et al.* 2003; Vigilante *et al.* 2004; Vigilante and Bowman 2004a; Vigilante and Bowman 2004b; Mucina and Daniel 2013).

Twenty-seven species of small mammal are currently known to occur in the NOK (Burbidge *et al.* 2008). Murid rodents are the most diverse family and account for 12 species. There are also seven carnivorous marsupial species (Dasyuridae), two bandicoot species (Peramelidae), two rock-wallaby species (Macropodidae), three possum species (Pseudocheiridae and Phalangeridae) and one species of glider (*Petaurus breviceps*, Petauridae) known from the NOK.

Some of the small mammal species have suffered range contraction, including the large rodents (*Mesembriomys macrurus, M. gouldii* and *C. penicillatus*) and golden bandicoots (*Isoodon auratus*) (Radford *et al.* 2014). The NOK is considered critically important for safeguarding these and other species at risk of extinction across northern Australia

(Fitzsimons *et al.* 2010; Corey *et al.* 2013). Recent observations have confirmed that all of the small mammal species persist within the major national parks in the NOK (Start *et al.* 2007; Corey *et al.* 2013), however, little information is available on their current presence beyond these protected areas (Turpin 2015). The three major national parks in the NOK are adjoined by a pastoral lease, Doongan Station. To date, no information on the status of small mammals on this privately leased station has been documented.

The aims of the current study were to (1) conduct faunal surveys on Doongan Station to establish baseline information on the occurrence of small mammal species, and (2) compare our findings to those on the adjacent national parks and to consider the possible reasons for any observed differences, and better understand faunal distributions across the NOK.

2.4 Methods

2.4.1 Study area

This study was conducted on Doongan Station, an area of approximately 3,400 km^2, in the NOK, Western Australia (Figure 7). This station is abutted by DRNP to the east and PRNP to the west, along with MRNP in the northwestern corner. The study region encompasses the Couchman and Foster Ranges, is bounded on the east by the Carson River and major watercourses include sections of the King Edward River and the Mitchell River. Doongan Station is a pastoral lease with free-roaming cattle (*Bos taurus*), with some stock reduction across the station during the study period. The station has been part of EcoFire, an early-dry-season prescribed burning program, from 2008 to 2014 (Legge *et al.* 2011b). The station lies within the Mitchell subregion of the NOK bioregion (Thackway and Cresswell 1995; Interim Biogeographic Regionalisation for Australia (IBRA7) 2015). Doongan Station is part of northern Australia’s tropical savanna and experiences a monsoonal climate with a rain dominated 'wet' season from November to April, and 'dry' season for the remainder of the year, with an average annual rainfall approximately 1000-1600 mm. Throughout the year, average temperatures range from 25-35 °C (Bureau of Meteorology 2015b) with high and low humidity in the wet and dry seasons respectively.

2.4.2 Field methods

Fifteen locations were selected for biological surveys, which included sampling for small terrestrial mammals (non-volant, <2kg) by trapping, spotlighting and searching. Selection criteria for locations included habitats (e.g. rainforest patches, sandstone escarpments), accessibility and proximity to potable water (Table 2 and Figure 7). Within each location, sampling was undertaken at several sites, which were selected to encompass local landscape and vegetation heterogeneity. During 11 sampling periods spread across nine years (2006-2014), 120 sites were sampled in 295 survey sessions (Table 3).

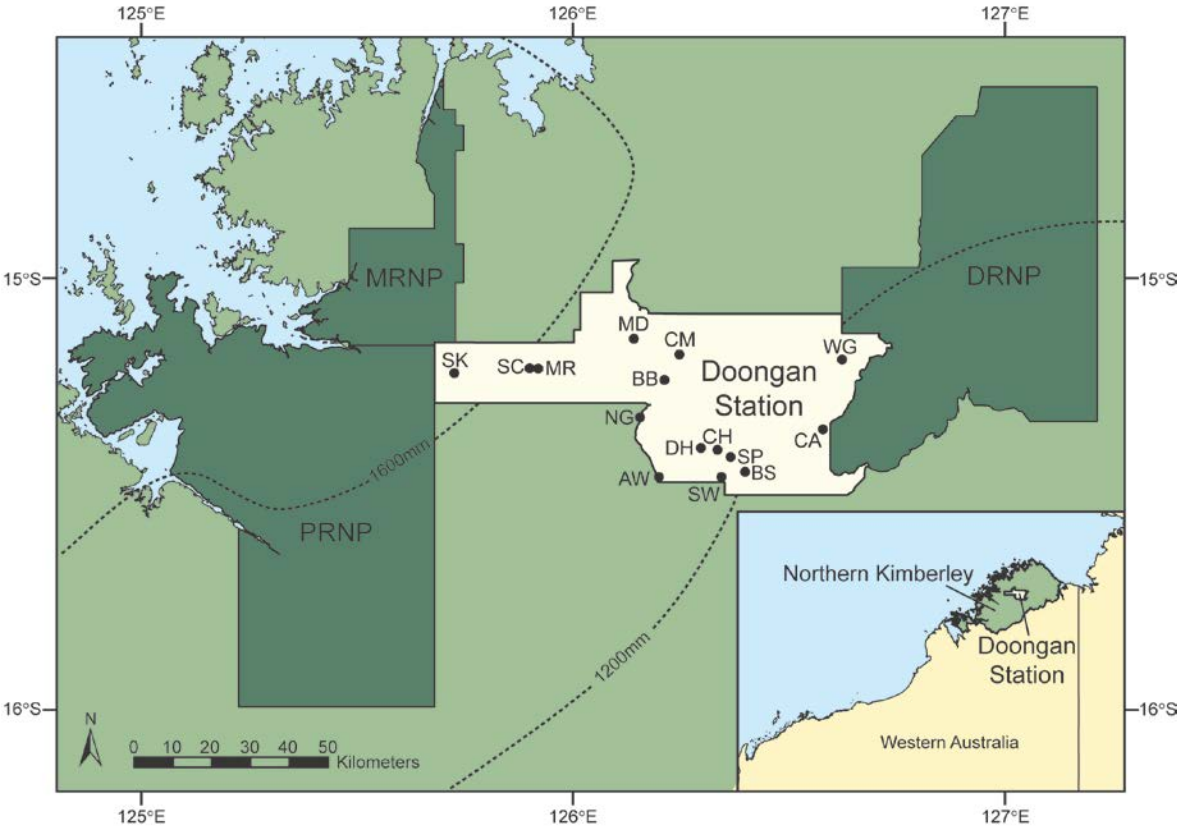


Figure 7. The study region, Doongan Station, in relation to three major parks in the Northern Kimberley (inset), Western Australia.

DRNP: Drysdale River National Park; MRNP: Mitchell River National Park; PRNP: Prince Regent National Park. See Table 2 for abbreviations and latitudes and longitudes.

Two types of treadle-style traps were used: medium ‘Elliott’ traps (10 x 10 x 33 cm) and wire cage traps (20 x 20 x 75 cm). These were each baited with a mixture of peanut butter, rolled-oats and honey. Traps were opened in the afternoon, checked the following morning and closed during the day. Pitfall traps were constructed with a 10 m x 30 cm drift fence and pitfalls were set in the centre of the drift fence at a depth of 50 cm, structurally supported using a 15 cm diameter PVC pipe with a flyscreen capped base inserted into the ground. Funnel traps were placed on both sides of the drift fences and covered with reflective foil insulation for protection from the sun. Both the pitfall and the funnel traps were checked periodically during the day. Spotlight surveys involved active nocturnal searching by foot. A larger biodiversity survey included diurnal searching, although this was targeted at herpetological species.

In 2006 and 2007, sites were surveyed along line transects (n=85) using a combination of Elliott, cage and pitfall traps laid approximately 20 m apart (10 to 40 traps per transect) for between three and six nights. During 2008 to 2014, sites were surveyed in quadrats (n=210) using quadrat-based methods (Woinarski *et al.* 1999b; NRETAS 2011). For each quadrat, 20 Elliott traps were placed around the perimeter (usually 50 x 50 m; 80 x 20 m for riparian sites) with a cage trap at each corner. One pitfall (terrain permitting) and two funnel traps were laid within the quadrat near each corner and drift fences were erected diagonally across the quadrat. For each survey period, the number of trap nights for each trap type is summarised in Table 3.

Broad topographic and floral descriptions of sites were carried out in 2006 and 2007. Commencing in 2008, more detailed, systematic habitat assessments were undertaken. These included scaled disturbance classifications of the impact of feral species and fire, landscape position, distance from current and permanent water, soil characteristics (type, texture, depth, and colour), ground cover, rock cover and vegetation profiles.

Fourteen broad habitat types were distinguished according to land system (Payne and Schoknecht 2011), landscape position, geology (Williams and Sofoulis 1967; Derrick 1969), surface rock type, soil color, soil depth and dominant vegetation. The number of sites, surveys and the trapping effort conducted within each broad habitat type are summarised in Table 4 and the corresponding habitat descriptions in Appendix 1. Different habitat types were present at each location (Table 2) and different combinations of locations and habitats were surveyed each year (Table 3).

Table 2. Coordinates of locations and the number of sites, collective survey sessions of sites and habitat types at each location on Doongan Station.

Habitat Types include blacksoil (BlS), laterite flats (LaF), laterite volcanic hills (LaV), lateritic creekline (LaC), monsoon forest (MoF), rainforest (RaF), rugged sandstone (RuS), sandstone outcrop (SaO), sandstone plains (SaP), sandstone riparian formation (SaC), volcanic hills (VoH), volcanic low woodland (VoW), volcanic riparian formation (VoR) and wetland (WeL).

Location Code	Location	Latitude	Longitude	Sites	Surveys	Habitat Types
AW	Andy's Waterhole	15˚27'S	126˚11'E	8	8	SaO, SaP, SaC
BB	Billabong	15˚13'S	126˚12'E	8	27	LaV, LaC, WeL
BS	Black Soil	15˚26'S	126˚23'E	9	14	BlS, LaC, SaO
CA	Carson River	15˚20'S	126˚34'E	8	16	MoF, RuS, SaO, VoR, WeL
CH	Cuckoo Hill	15˚23'S	126˚20'E	1	9	LaV
CM	Couchman	15˚07'S	126˚14'E	11	33	RuS, SaP, SaC, WeL
DH	Doongan Homestead	15˚23'S	126˚17'E	5	28	BlS, LaF, LaC, WeL
MD	Mitchell River Road	15˚07'S	126˚08'E	9	41	RuS, SaP, SaC, WeL
MR	Mitchell River	15˚11'S	125˚55'E	13	17	RuS, SaP, SaC
NG	Nagomorro	15˚18'S	126˚90'E	8	18	RuS, SaP, SaC
SC	Spring Creek	15˚11'S	125˚54'E	12	29	RaF, RuS, SaO, SaP, SaC, VoW, WeL
SK	Skull Creek	15˚12'S	125˚43'E	8	8	RaF, SaP, VoW, WeL
SP	Stony Plains	15˚24'S	126˚21'E	1	9	LaV
SW	Southern Windmill	15˚27'S	126˚20'E	9	28	LaV, LaC, SaO
WG	Woongaroodoo Gorge	15˚10'S	126˚37'E	10	10	VoH, VoW, VoR
	Total			120	295	

Table 3. Survey effort each year from 2006 to 2014 on Doongan Station.

Locations include Andy's Waterhole (AW), Billabong (BB), Black Soil (BS), Carson River (CA), Cuckoo Hill (CH), Couchman (CM), Doongan Homestead (DH), Mitchell River Road (MD), Mitchell River (MR), Nagomorro (NG), Spring Creek (SC), Skull Creek (SK), Stony Plains (SP), Southern Windmill (SW) and Woongaroodoo Gorge (WG).

Year	Period	Season	Sites	Trap Nights				Spotlight Minutes	Locations
				Elliott	Cage	Pitfall	Funnel		
2006	July - August	Dry	11	3330	855	192	0	1200	BS, CH, DH, NG, SP
2006	December	Wet	6	250	150	0	0	120	CH, DH, SP
2007	February	Wet	6	400	160	160	0	450	BS, CH, DH, NG, SP
2007	June - August	Dry	62	4129	1216	56	0	3240	BS, CM, CH, DH, MR, NG, SC, SP, WG
2008	April - May	Dry	40	2484	1148	266	0	1200	BB, BS, CM, CH, DH, NG, SK, SP, SW
2009	May - June	Dry	16	1280	256	232	512	480	AW, MD
2010	May - June	Dry	24	1920	368	340	768	480	BB, CM, CH, DH, MD, NG, SW
2011	May	Dry	32	2560	508	404	1024	640	BB, BS, CH, DH, MD, SC, SP
2012	May - June	Dry	32	2560	500	356	1024	640	CM, CH, DH, MD, NG, SP, SW
2013	May - June	Dry	33	2640	528	360	1056	660	BB, CA, MD, SC
2014	June	Dry	33	2600	524	336	1056	660	CA, CM, CH, DH, NG, SP, SW
Total			295	24153	6213	2702	5440	9770	

Table 4. Survey effort conducted in the 14 broad habitat types on Doongan Station including the number of locations, sites, and collective survey sessions of sites.

				Trap Nights				Spotlight Minutes
Broad Habitat Type	Locations	Sites	Surveys	Elliott	Cage	Pitfall	Funnel	
Blacksoil (BlS)	2	5	14	904	356	120	160	1110
Laterite flats (LaF)	1	2	6	424	98	64	96	90
Laterite volcanic hills (LaV)	4	13	51	4326	1250	592	928	1190
Lateritic creekline (LaC)	4	5	21	2726	586	308	416	740
Monsoon forest (MoF)	1	2	4	320	64	0	128	80
Rainforest (RaF)	2	3	7	633	178	4	64	220
Rugged sandstone (RuS)	6	17	41	3808	899	304	896	640
Sandstone outcrop (SaO)	5	9	14	984	204	36	256	320
Sandstone plains (SaP)	7	24	52	4166	1099	650	1120	1090
Sandstone riparian formation (SaC)	6	16	34	1960	550	228	544	430
Volcanic hills (VoH)	1	1	1	96	12	0	0	840
Volcanic low woodland (VoW)	3	7	9	564	149	60	64	130
Volcanic riparian formation (VoR)	2	7	8	490	104	32	64	1870
Wetland (WeL)	7	9	33	2752	664	304	704	1020
Total		120	295	24153	6213	2702	5440	9770

2.4.3 Captured animals

Morphological measurements were recorded and tissue biopsies were taken from the ear of all captured mammals for use in genetic studies and for identification of unknown individuals. To confirm or assist with field identification of species, hair samples were collected from the mid-dorsal region and photographs of footpads and tail scales were taken for rodents. Animals were released at the site of capture. Recaptured animals were identified from marks indicating a previous ear biopsy and released immediately. Nomenclature of species follows Van Dyck and Strahan (2008).

2.4.4 Comparison of Doongan Station and NOK

The presence of species on Doongan Station was qualitatively compared with those from the three major national parks in the NOK. Species presence was ascertained from previous surveys of MRNP, PRNP and DRNP (McKenzie *et al.* 1975a; McKenzie *et al.* 1975b; Kitchener *et al.* 1981; Bradley *et al.* 1987; Friend *et al.* 1991; Start *et al.* 2007).

2.5 Results

2.5.1 Doongan Station

In total, 750 small mammals were captured between 2006 and 2014 (Table 5). These included records of 13 species, along with 44 records of unidentified rodent species and one sighting of a pebble-mound characteristic of *P. johnsoni*. Our results are summarised in Tables 5 - 7. Critical weight range (CWR; 35-5500 g) (Burbidge and McKenzie 1989) species accounted for 10 of the 13 species confirmed to occur on Doongan Station and three species below CWR were also captured (Table 5). Thirteen of the CWR species known to occur in the region were not detected (Table 8).

The detection of small mammals varied between capture methods. Elliott traps yielded the highest trap success (2.7 captures per 100 trap nights), followed by pitfall traps (1.6 captures per 100 trap nights) and cage traps (0.7 captures per 100 trap nights). Only four individuals (one each of *S. virginiae*, *P. maculata*, *P. nanus* and *P. delicatulus*) were recorded in spotlight surveys of sites. Two species (*Petropseudes dahli* and *Petaurus* *breviceps*) were not trapped but were opportunistically detected by spotlight outside of the survey sites. No captures were made in funnel traps and these have been excluded from any further analyses. Fourteen hand-captures were made opportunistically. Four records (one *L. lakedownensis,* two *P. delicatulus* and one *R. tunneyi*) were excluded from trap success analysis due to missing trapping method data.

Trap success varied annually, with the highest dry season trap success being observed in 2013 (4.9 captures per 100 trap nights) and the lowest being observed in 2008 (0.33 captures per 100 trap nights; see Table 6). The highest overall trap success was observed in the wet season during February 2007 (5.97 captures per 100 trap nights) with only six sites being surveyed across this period (Table 3) and rodents at two sites comprising 73% of these records. The greatest species richness was recorded in June-August 2007, whilst the lowest richness was recorded in December 2006 which coincided with the least trapping effort (see Table 6). None of the small mammal species were detected in every trapping period. When the quadrat trapping method was compared alone (2008-2014), the highest overall capture rate was recorded in 2013. During this time, trap success increased, notably in 2013 to 4.8%, but decreased in 2014 for all species except *Z. argurus* and *L. lakedownensis* (not detected in 2013). The highest trap success was also observed in 2013 for *P. delicatulus, P. nanus, R. tunneyi, S. virginiae* and *I. macrourus* (Table 6).

2.5.1.1 Muridae

Most individuals captured were murid rodents, accounting for 80% of the records (597 records; see Table 5). Muridae was both the most species diverse and the most abundant group detected on Doongan Station, being recorded across all 14 habitat types (Table 7). *Pseudomys nanus* was the most widely recorded small mammal species (Table 5) and was detected in all trapping periods except 2008 (Table 6). The greatest numbers of individuals were recorded on two lateritic volcanic sites (n=26 and n=18). *Rattus tunneyi* was the most frequently recorded species and was similarly detected in all trapping periods, except December 2006 and April – May 2008 (Table 6). It was also recorded in the greatest number of broad habitat types (Table 7). *Zyzomys argurus* was also frequently detected (Table 5), predominantly on King Leopold Sandstone country but it was also recorded on Carson Volcanics (Table 7).

Table 5. Small mammals recorded between 2006 and 2014 on Doongan Station.

Superscript indicates the number of opportunistic records not within the survey sites.* denotes a suspected pebble-mound. + denotes critical weight range species.

Species	Locations (n=14)	Sites (n=120)	Surveys (n=295)	Individuals
Muridae (Murinae)				
Leggadina lakedownensis	8	16	24	35^{1}
Pseudomys delicatulus	11	27	38	69^{2}
Pseudomys nanus^{+}	11	49	64	141^{3}
Melomys burtoni^{+}	1	1	2	2
Rattus tunneyi^{+}	12	42	58	172
Zyzomys argurus^{+}	5	26	28	128
Hydromys chrysogaster^{+}	2	2	2	3^{2}
Rodent sp.				47
Pseudomys johnsoni	1	*	*	*
Dasyuridae				
Planigale maculata	6	7	7	8
Sminthopsis virginiae^{+}	11	29	47	125
Dasyurus hallucatus^{+}	2	2	2	2
Peramelidae				
Isoodon macrourus^{+}	3	8	11	18
Pseudocheridae				
Petropseudes dahli^{+}	1	-	-	0^{1}
Petauridae				
Petaurus breviceps^{+}	2	-	-	0^{2}
Total				750^{11}

Table 6. Trap success (%) for small mammals from 2006 to 2014 on Doongan Station.

'-' denotes no records and mean indicates trap success across sites ± standard error. See Table 3 for the effort and broad habitat types surveyed each year.

Species	2006 (Jul)	2006 (Dec)	2007 (Feb)	2007 (Jul)	2008 (Apr)	2009 (May)	2010 (May)	2011 (May)	2012 (May)	2013 (May)	2014 (Jun)
Muridae (Murinae)											
Leggadina lakedownensis	0.09	1.00	0.83	-	-	-	0.08	0.12	0.12	-	0.17
Pseudomys delicatulus	0.21	-	0.28	0.09	0.03	0.40	0.23	-	0.32	0.48	0.23
Pseudomys nanus	0.09	0.75	1.67	0.67	-	0.06	0.34	0.35	0.47	0.71	0.58
Melomys burtoni	-	-	-	0.04	-	-	-	-	-	-	-
Rattus tunneyi	0.18	-	1.94	0.19	-	0.28	0.80	0.72	0.38	1.56	0.49
Zyzomys argurus	0.07	-	0.69	1.33	0.08	-	0.04	0.03	0.12	0.45	0.66
Hydromys chrysogaster	-	-	-	-	-	-	-	0.06	-	-	-
Rodent sp.	0.50	0.00	0.42	0.22	0.08	0.00	0.04	0.03	0.06	0.06	0.00
Dasyuridae											
Planigale maculata	0.02	-	0.14	0.02	-	-	0.04	0.03	0.03	-	-
Sminthopsis virginiae	0.05	-	-	0.07	0.15	-	0.08	0.52	0.47	1.47	0.69
Dasyurus hallucatus	-	-	-	0.02	0.03	-	-	-	-	-	-
Peramelidae											
Isoodon macrourus	-	-	-	0.20	-	-	-	0.03	-	0.14	-
Total	1.21	1.75	5.97	2.85	0.33	0.74	1.64	1.87	1.96	4.88	2.83
Mean	n.a.	n.a.	n.a.	n.a.	0.4±0.15	0.8±0.29	1.6±0.46	2.2±0.48	2.0±0.36	4.8±0.93	2.9±0.58

Table 7. Number of sites in the 14 broad habitats where small mammal species were detected on Doongan Station.

Habitats include blacksoil (BlS), laterite flats (LaF), laterite volcanic hills (LaV), lateritic creekline (LaC), monsoon forest (MoF), rainforest (RaF), rugged sandstone (RuS), sandstone outcrop (SaO), sandstone plains (SaP), sandstone riparian formation (SaC), volcanic hills (VoH), volcanic low woodland (VoW), volcanic riparian formation (VoR) and wetland (WeL). Total Habitats indicates the number of different habitats species were observed in. See Table 4 for total number of sites (n) for each broad habitat type. See Appendix 1 for descriptions of broad habitat types.

Species	BlS	LaF	LaV	LaC	MoF	RaF	RuS	SaO	SaP	SaC	VoH	VoW	VoR	WeL	Total Habitats
Muridae (Murinae)															
Leggadina lakedownensis	1	1	6	2				1	3					2	7
Pseudomys delicatulus	1	1	2	2			4	1	9	5				2	9
Pseudomys nanus		2	9	5	1	1	6	4	9	4		1	2	5	12
Melomys burtoni						1									1
Rattus tunneyi			5	4		1	4	1	12	5	1	1	3	5	11
Zyzomys argurus					2		10	2	4	4	1		2	1	8
Hydromys chrysogaster						1	1								2
Dasyuridae															
Planigale maculata			3	1	1				1	1					5
Sminthopsis virginiae	2		7	4		1			4	3		1		7	8
Dasyurus hallucatus									1	1					2
Peramelidae															
Isoodon macrourus						2			2			1		3	4

The thirty-five records of *L. lakedownensis* (Table 5) were predominantly obtained from woodlands, on gentle slopes and plains, including nineteen of these being recorded across six laterite volcanic hill sites (Table 7). *Melomys burtoni* was the least recorded murid rodent, with only two individuals captured at a single site on the edge of a small, dense rainforest patch adjacent to a creekline. The two captures of *H. chrysogaster* also occurred in this rainforest patch. Three additional *H. chrysogaster* were recorded from opportunistic sightings, two of which were outside of the targeted survey effort.

2.5.1.2 Dasyuridae

In total, 135 dasyurids of at least three different species were recorded (see Tables 5 - 7). *Sminthopsis virginiae* was both the most widely observed (29 sites) and the most frequently recorded dasyurid species. It was predominantly captured in bog complexes, flooded grasslands and creeklines, as well as lateritic volcanic hills sites (Table 7). The two *D. hallucatus* captures were from rugged boulder country, with one captured on a sandstone scree whilst the other was in a deep gorge (Table 7). These were on the west of the property, at the two sites most proximal to PRNP. Eight *P. maculata* were recorded in open woodlands, on blacksoil (cracking clay) and lateritic and sandstone loams, as well as one monsoon forest site (Table 7).

2.5.1.3 Peramelidae

Isoodon macrourus was the only bandicoot species detected and it was only recorded during three of the survey periods, across four habitat types (see Tables 5 - 7). These were predominantly in open woodlands to open forests with deep soils, as well as two rainforests (Table 7).

2.5.2 Doongan Station and the NOK

The small mammal species recorded from the three major national parks in the NOK, together with those recorded in this study, are summarised in Table 8. MRNP had the highest species richness, with 10 species known to occur in MRNP not detected in this study. *Hydromys chrysogaster* is the only species recorded on Doongan Station that has not been detected within MRNP. Similar to MRNP, seven species known to occur in PRNP were not detected on Doongan Station. Conversely, four species detected in this study have not been recorded within PRNP. DRNP had the lowest species richness of small mammals across all the NPs and compared to Doongan Station. *Pseudantechinus ningbing* is the only species that has been recorded on DRNP that was not recorded on Doongan Station. Five species that occur on Doongan Station have not been detected in DRNP.

2.6 Discussion

We present findings from long-term small terrestrial mammal fauna surveys from a previously unsurveyed pastoral station in the NOK. The small mammals detected on Doongan Station were somewhat comparable with those known to be present in the adjacent national parks, and their associations with habitats were consistent with those previously reported in the NOK and elsewhere in northern Australia. The presence/absence of each species is explored in more detail below.

Pseudomys nanus and *R. tunneyi* are both habitat generalists, and have been observed in a wide range of habitats including grasslands, open woodlands and creeklines (Cole and Woinarski 2002; Firth *et al.* 2006). Our results also support their presence across broad habitat types (Table 7). *Zyzomys argurus* inhabits rocky boulder country (Woinarski *et al.* 2014) and was similarly observed in King Leopold sandstone complexes in this study. The detection of these three species was not surprising, as they, along with *P. delicatulus*, are the only small mammal species which have been recorded in all of the national parks surveyed in the NOK (Table 8) and they are considered common across their respective ranges (Ford 2008).

Leggadina lakedownensis is widely distributed across northern Australia, yet, with the exception of the Thevenard Island population (Moro and Morris 2000a; Moro and Morris 2000b), this species remains poorly known (Kutt and Kemp 2005). Its widespread occurrence on Doongan Station is likely due to the prevalence of extensive grassland and savanna, as suggested to also be the case for DRNP (McKenzie *et al.* 1975b). *Pseudomys delicatulus* is known to prefer open woodlands, including riparian zones and hummock grasslands on sandy or loamy soils, which was reflected in this study, although we also detected them in sandstone habitats (Table 7).

Table 8. Small mammal species known to occur in the Northern Kimberley showing those recorded in this study and the adjacent national parks.

Species list derived from Burbidge *et al.* (2008). A= Kitchener *et al.* (1981); B= Bradley *et al.* (1987); C= McKenzie *et al.* (1975a); D= McKenzie *et al.* (1975b); E= Friend *et al.* (1991); F= Start *et al.* (2007). * denotes unconfirmed. + denotes critical weight range species.

Species	MRNP	PRNP	DRNP	Doongan Station
Muridae (Murinae)				
Leggadina lakedownensis	B	-	F	X
Pseudomys delicatulus	A, B	C, F	D	X
Pseudomys johnsoni	B	-	-	*
Pseudomys nanus^{+}	A, B, F	C	D	X
Conilurus penicillatus^{+}	A, B, F	C, F	-	-
Mesembriomys gouldii^{+}	B	-	-	-
Mesembriomys macrurus^{+}	A, B, F	C, E, F	-	-
Melomys burtoni^{+}	B, F	C, F	-	X
Rattus tunneyi^{+}	A, B, F	C, F	D, F	X
Zyzomys argurus^{+}	A, B, F	C, E, F	D, F, E	X
Zyzomys woodwardi^{+}	A, B, F	C, E, F	-	-
Hydromys chrysogaster^{+}	-	C, F	D, F	X
Dasyuridae				
Phascogale [tapoatafa]$^{+}$	B	-	-	-
Pseudantechinus ningbing	B	-	F	-
Sminthopsis butleri	-	-	-	-
Sminthopsis macroura	-	-	-	-
Sminthopsis virginiae^{+}	A, B, F			X
Dasyurus hallucatus^{+}	A, B, F	C, E, F		X
Planigale maculata	A, B		D	X
Peramelidae				
Isoodon auratus^{+}	F	C, F	-	-
Isoodon macrourus^{+}	A, B, F	C, E, F	-	X
Macropodidae				
Petrogale burbidgei^{+}	A, F	F	-	-
Petrogale concinna^{+}	-	C, F	F	-
Pseudocheiridae				
Petropseudes dahli^{+}	-	C, F	-	X
Phalangeridae				
Trichosurus vulpecula^{+}	A, B	-	-	-
Wyulda squamicaudata^{+}	A, B, F	C, F	-	-
Petauridae				
Petaurus breviceps^{+}	A, F	-	D	X

Hydromys chrysogaster is known to be difficult to capture even when its presence has been confirmed at a site (Gibson and McKenzie 2012). Because it has a largely carnivorous diet, using meat or fish baited traps may have been a more productive method of detecting this species (Laurance 1992). It is likely that the abundance of *H. chrysogaster* is higher than our three records suggest and false absences due to failed detection have been observed in this study. Conversely, the rarity of *M. burtoni* is more likely a consequence of both habitat restrictions and limited trapping effort within its preferred habitat. Throughout its range, *M. burtoni* is known to inhabit dense forest, riparian and swamp habitats, and mangroves (Kerle 2008), often close to water and supporting *Pandanus* spp. which are often utilised for their nesting (Begg *et al.* 1983). Only two small monsoon forest patches were surveyed in this study and it is likely there is limited availability of habitat on Doongan Station.

The presence of *P. johnsoni* was not confirmed. *Pseudomys johnsoni* has been found in a wide variety of habitats from open woodland to spinifex grasslands and sparse to dense understoreys. In stony habitats this species uses pebbles to construct mounds near the entrance to its burrow system (Ford and Johnson 2007). Only one site in this study had mounds characteristic of this species on a seemingly suitable substrate, however, its presence could not be confirmed.

The three species of tree-rats that were not detected on Doongan Station (*M. macrurus*, *M. gouldii*, and *C. penicillatus*) have undergone decline in northern Australia (Woinarski *et al.* 2014). *Mesembriomys macrurus* was historically distributed in the Northern Territory but has not been recorded there since 1969 - habitat loss and predation by feral species have been attributed to causing its decline (Woinarski 2000). Similarly, *M. gouldii* has disappeared from the drier parts of its range in Western Australia (Watts and Aslin 1981; Woinarski *et al.* 2014). *Conilurus penicillatus* is known from fewer than ten localities and has always been rare in Western Australia (NOK) but it has also suffered major declines in the Northern Territory (Firth *et al.* 2010). In recent years, all of the records of these three rodents have come from high-rainfall areas dominated by country sufficiently rugged to limit fire intrusion and prevent intensive pastoral usage (Woinarski *et al.* 2014). Similarly, a number of other species known to inhabit such rocky areas are now largely confined to, or only known from, the high rainfall areas of the NOK, and were not detected on Doongan Station. These include the possums (*P. dahli* and *W. squamicaudata*) and small rock-wallabies (*P. burbidgei* and *P. concinna*).

Also restricted to the high rainfall areas, *Z. woodwardi* is endemic to the Kimberley region, including eight islands (Begg 1981; Gibson and McKenzie 2012). This rodent species is considered to be patchily distributed, but locally common. Its habitat preferences overlap with those of *Z. argurus* and *D. hallucatus*, although *Z. woodwardi* tends to prefer wetter and more heavily vegetated areas (Begg 1981). Spatial separation between *Z. argurus* and *Z. woodwardi* has been observed whereby *Z. argurus* has been recorded in *Z. woodwardi* habitat when *Z. woodwardi* is absent (Begg 1981). The prevalence of *Z. argurus* in this study could suggest the likely absence of *Z. woodwardi* in those areas. However, the lack of survey effort in its favoured habitats, including rugged boulder screes, vine thickets and closed forest, may have limited its detection.

Sminthopsis virginiae has rarely been observed in the NOK despite being considered common across its range (Woolley 2008c). Little is known of the ecology of *S. virginiae*, however Braithwaite and Lonsdale (1987) suggest from observations in the Northern Territory, that nearby foraging areas with a suitable graminoid ground layer are required for *S. virginiae* to be present, whilst on Melville Island (Northern Territory) it has been associated with swamps (Firth *et al.* 2006). Within the MRNP, this species was observed in sites that included a dense grass layer (Bradley *et al.* 1987). In the current study, *S. virginiae* was recorded in similar habitats (see Table 7 for habitats). This study records the most abundant record of *S. virginiae* populations in the NOK. The absence of the two other dunnart species was unsurprising; *S. butleri* is known from only one location in the NOK (Woolley 2008a) and *S. macroura* from only the southern margin of the NOK (Morton and Dickman 2008).

Planigale maculata is currently recognised as the only *Planigale* species occurring within the NOK. However, there is some taxonomic uncertainty within this genus and the current status and distribution of this species requires revision (Blacket *et al.* 2000). Taxonomic investigation is currently being undertaken (K. Armstrong pers. comm.). The records of *P. maculata* from MRNP and DRNP were from low woodland over laterite and a shrubland over tussock grass with occasional sandstone outcrops (Kitchener *et al.* 1981; Bradley *et al.* 1987), and our records were in similar habitat to these findings.

Dasyurus hallucatus is known to prefer rocky habitats such as escarpments, but is not necessarily restricted to them (McKenzie *et al.* 1975a; Oakwood 1997). Accordingly, our two *D. hallucatus* records were both within rocky boulder country. This species was once widely distributed across northern Australia, however, range contraction is considered to have been caused by the prevalence of cattle and fire, with savanna populations being considered to be the most vulnerable to decline (Braithwaite and Griffiths 1994; Oakwood 2002). More recently, the cane toad invasion has further contributed to declines of this species (Shine 2010); the cane toad is not yet present on Doongan Station but it has recently invaded the NOK (DPAW 2015a). DRNP is the only NOK reserve to date in which *D. hallucatus* has not been recorded. For the most part, DRNP comprises less dissected savanna, however, there are isolated erosional escarpments and the western edge of the park comprises the rugged King Leopold Sandstones of the Prince Regent Plateau. Accordingly, lack of rocky habitat is unlikely to be limiting. The species was not detected in similar habitat during recent camera trapping in the Cockburn Range (east of the DRNP) (Turpin 2015) although it has been detected there within the last 10 years (DPAW 2015b). Isolated rugged areas may not be sufficient to sustain populations if the surrounding savanna is disturbed by fire and/or cattle pressure (Hill and Ward 2010); feral cattle were either present, or sign of them was observed, at all DRNP sites in 1975 (McKenzie *et al.* 1975b). This may also explain the lack of *D. hallucatus* records on Doongan Station, an active pastoral lease.

Further investigation is needed to explain the absence of two other dasyurid species (*P. [tapoatafa]* and *P. ningbing*) on Doongan Station. *Phascogale [tapoatafa]* is largely arboreal, and in contrast to the arboreal rodents, rarely comes to the ground and thus is difficult to detect or trap (Traill and Coates 1993; Start *et al.* 2007). Recent range contraction of *P. [tapoatafa]* is known to have occurred in the Kimberley and numbers can be low in apparently suitable habitat (Woinarski 2014). In the NOK, *P. ningbing* has been recorded only on DRNP (Start *et al.* 2007) and Augustus and Heywood Islands, but it has been recorded throughout the Kimberley region (DPAW 2015b). It has been associated with both sandstone and limestone rocky outcrops, but little is known about its ecology (Fisher *et al.* 2000; Woolley 2008b), thus its apparent absence from Doongan Station cannot be inferred.

Only two bandicoot species (*I. macrourus* and *I. auratus*) are known to occur in the NOK. The rarity of *I. macrourus* on Doongan Station may be due to our limited survey effort within vine thicket, rainforest and structurally complex sites on deep alluvial or heavy clay soils, which it is known to inhabit. *Isoodon macrourus* has been observed to be declining in northern Australia (Woinarski *et al.* 2014) which may also help explain its rarity on Doongan Station. However, without historical records, this cannot be determined. *Isoodon auratus* has also been declining in northern Australia (Woinarski *et al.* 2014) and was not detected in this study. The Kimberley region is now the only mainland region in which *I. auratus* is known to persist, along with the island populations of Marchinbar Island (Northern Territory), four NOK islands (Augustus, Uwins, Lachlan and Storr) and two islands off the Pilbara coast (Barrow and Middle Islands) (Gibson and McKenzie 2012). *Isoodon auratus* is now limited to rocky sandstone habitat and vine thickets with medium to high rainfall (700 to 1200 mm) and it has been found to nest in thick *Triodia* where low heath or shrubland on sand or sandstone is adjacent for foraging (Palmer *et al.* 2003). Such substratum can be created by fine-scaled fire mosaics (Price *et al.* 2003); on Marchinbar Island, the highly dissected landscape creates a similar vegetation mix and may explain its occurrence there (Southgate *et al.* 1996). Large-scale fire is considered a major contributor to its decline in northern Australia (Woinarski *et al.* 2014).

2.6.1 Doongan Station and the NOK

The comparison of the presence of small terrestrial mammals on Doongan Station to the surrounding national parks in the NOK is limited to qualitative comparisons. Earlier surveys of the national parks were primarily inventorial, did not provide accurate details of trapping effort and employed a variety of types of traps and methods. Start *et al.* (2007) have previously recognised this caveat when revisiting historically surveyed sites in the NOK. More recent surveys are more specific in their methods, however, these surveys were limited to only a few sites within each national park (Start *et al.* 2007; Radford 2012; Corey *et al.* 2013).

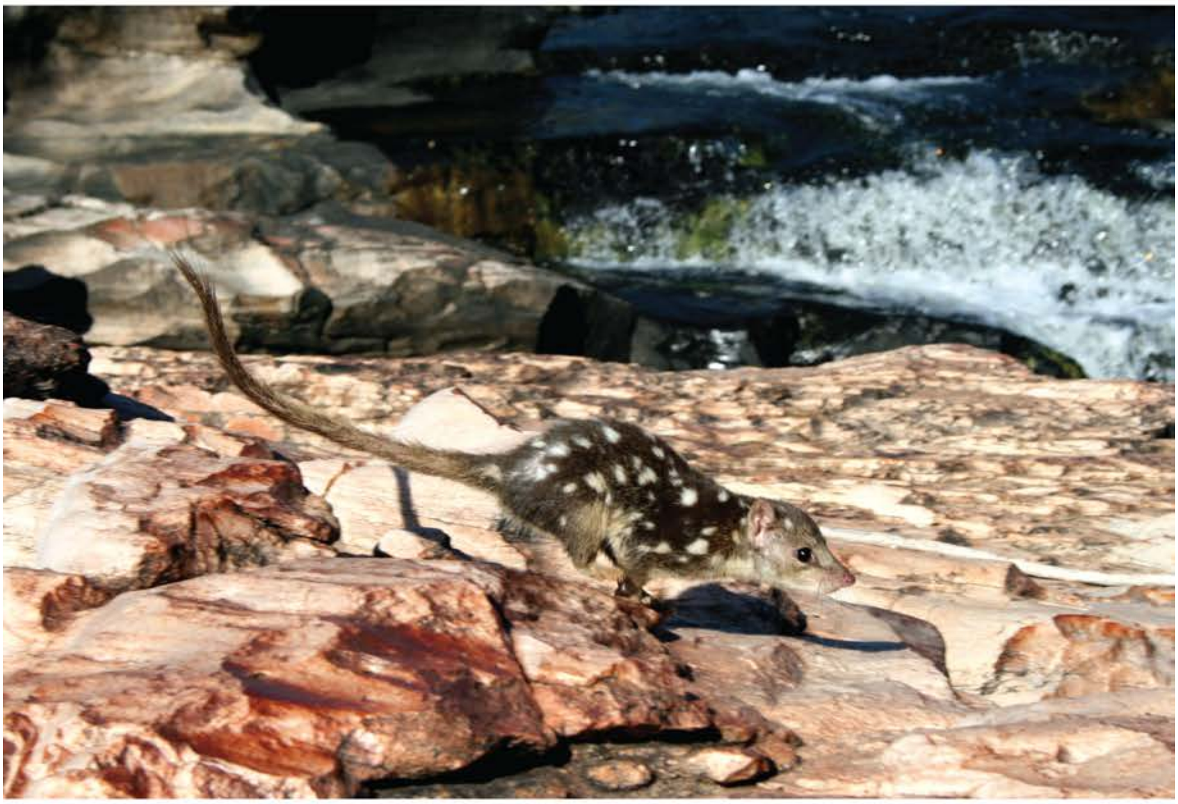
In northern Australia, higher rainfall areas tend to support both a higher abundance and a greater diversity of fauna (Radford *et al.* 2014; Turpin 2015). Rainfall has been found to affect both species richness and abundance within the King Leopold Ranges (western Central Kimberley and northern Dampierland) (Start *et al.* 2012a). The richness of small mammals detected on Doongan Station was lower than those reported in the national parks to the north (MRNP) and west (PRNP) but higher than east of Doongan (DRNP) (Table 8). Interestingly, this corresponds to a rainfall gradient whereby there is a northwest – southeast decrease in both the amount and the intensity of rainfall in the Kimberley (Bureau of Meteorology 2015b). Kitchener *et al.* (1981) suggest that "the wide range of the physiography in the area coupled with a protracted wet season" explains the high species richness they observed in MRNP. It is likely that the assimilation of lateritics, dissected sandstone and volcanics contributes to the heterogeneity of MRNP and PRNP to a greater extent than on Doongan Station and DRNP. This supports the hypothesis of Kitchener *et al.*'s (1981), indicating that along with rainfall, the ruggedness and landscape heterogeneity provided by the more coastal and near-coastal areas within MRNP and PRNP afford more protection, and refugia (Moritz *et al.* 2013), and thus greater species richness.

Monitoring in the NOK national parks in 2011 and 2012 has shown no evidence of collapse in the mammal fauna (Corey *et al.* 2013). The mean trap success reported by Corey *et al.* (2013) in 2011 and 2012 was approximately 10%. Severe declines were identified in Kakadu National Park when trap success per plot was approximately < 2% (Woinarski *et al.* 2010). The mean trap success recorded on Doongan Station was < 2% (Table 6) for four of seven years between 2008 and 2014, using comparable trapping methods to those of both Corey *et al.* (2013) and Woinarski (2010). This trap success suggests that small mammal abundance on Doongan Station is particularly low, but without historical data the significance of this cannot be determined.

Further analysis of the temporal changes is required, although these were largely explained by large fluctuations of a few species. The 2013 boom may be the result of exceptionally high rainfall during the 2010-2011 wet season followed by above average rainfall in 2011-2012, however this is speculative. It may also be due to sampling bias by unintentionally sampling a suite of particularly productive sites, as the individual sites may vary in quality. The changes in trapping success could also possibly be due to large scale elements, such as fire and grazing pressure, which have not been measured here. Changed fire regimes, the prevalence of cattle and other introduced species, especially cats (*Felis catus*), are considered to be major influences in northern Australia (Woinarski 2014), particularly the compounded and synergistic effects of these variables (Fitzsimons *et al.* 2010; McGregor *et al.* 2014). It is probable that cattle grazing and fire regime have contributed to the low trap success. However, detailed understanding of how these variables influence the small mammal fauna in the NOK is impeded by inadequate baseline and temporal data. Further investigation of changes on Doongan Station is beyond the scope of this paper, but is currently in progress, which together with studies on other pastoral, savanna areas, will provide an important perspective on these complex interactions.

There is need for further research using regionally consistent study methods for establishing baselines, long-term monitoring and improving our understanding of the small mammal fauna in the NOK, including the biodiversity value of pastoral land as intermediaries or corridors between national parks (Department of Environment and Conservation 2011; Moritz *et al.* 2013). Cost is often prohibitive for investigating such remote and inaccessible areas. However, improved knowledge would greatly increase the capacity to prioritise management activities, including across lands of different tenure. Elucidation and mitigation of the factors having the greatest impact on small mammals in this region will be necessary for their future persistence and conservation.

Chapter 3
The occurrence and relative abundance of small terrestrial mammals on Theda Station in the Northern Kimberley, Western Australia



Northern Quoll
Dasyurus hallucatus

The occurrence and relative abundance of small terrestrial mammals on Theda Station in the Northern Kimberley, Western Australia

Liberty G.M. Olds[A,I], Cecilia Myers[B], Henry Cook[C], Brendan Schembri[D], Christopher Jackson[E], Nick Evans[F], Brian Charles[F], Rowan Waina[F], William G. Breed[G], David A. Taggart[A,H]

[A] School of Biological Sciences, University of Adelaide, Adelaide, SA, 5000, Australia

[B] Dunkeld Pastoral Company Pty Ltd, Dunkeld, Vic, 3294, Australia

[C] Cairns, Qld, 4870

[D] Rural View, Qld 4740

[E] Cranebrook, N.S.W. 2749

[F] Kalumburu Remote Community, Kalumburu, WA, 6740

[G] School of Medicine, University of Adelaide, Adelaide, SA 5000

[H] Fauna Research Alliance Ltd, P.O. Box 98, Callaghan, NSW, Australia, 2308

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3.1 Statement of authorship

By signing the Statement of Authorship, each author certifies that their stated contribution to the publication is accurate and that permission is granted for the publication to be included in the candidate's thesis.

Liberty Olds: (Candidate) ______________________ Date:__________________

Small mammal trapping, data collection, habitat assessments, data analysis, preparation of the full manuscript including all Tables and Figures, and acted as the corresponding author.

Cecilia Myers: Date: 17/4/16

Provided on-ground expertise, land management, field support and data collection.

Henry Cook: Date: 14/4/2016

Provided field support and data collection.

Brendan Schembri: Date: 12/4/16

Provided field support and data collection.

Christopher Jackson: Date: 28/04/16

Provided field support and data collection.

Nick Evans: _ Date: 17/4/16

Provided field support and data collection.

Brian Charles: _ Date: 17/4/16

Provided field support and data collection. Signed by Cecilia Myers on behalf of Brian Charles.

Rowan Waina: _ Date: 26/4/2016

Provided field support and data collection. Signed by David Taggart on behalf of Rowan Waina.

William G Breed: _ Date: 26/4/16

Provided rodent identification support and supervised the direction of the study.

David Taggart: _ Date: 26/4/2016.

Provided field support, data collection and manuscript revision.

3.2 Abstract

Significant knowledge gaps currently exist regarding the small mammals in the Northern Kimberley (NOK) bioregion. Theda Station is a previously un-surveyed pastoral lease in the NOK. The aim of the current study was to determine the presence of small mammals (non-volant, <2kg) on Theda Station and to compare these findings with those recently obtained on the adjacent Doongan Station. Between 2006 and 2014, a total of 226 site surveys were conducted across 69 sites, with over 26 000 trap nights and encompassing a range of habitats. Thirteen of the 27 small mammal species known to occur in the NOK were detected. Four species (*Pseudomys nanus*, *Rattus tunneyi*, *Zyzomys argurus* and *Sminthopsis virginiae*) were common, five species (*Pseudomys delicatulus*, *Pseudantechinus ningbing*, *Dasyurus hallucatus*, *Isoodon macrourus* and *Petropseudes dahli*) were detected less frequently, and four species (*Leggadina lakedownensis*, *Hydromys chrysogaster*, *Planigale maculata* and *Petaurus breviceps*) were detected infrequently. Our study provides important baseline records for small mammals in this region. It also highlights the lack of detailed knowledge of both the presence of, and temporal fluctuations in, the region's small mammal fauna. This study supports a non-uniform distribution of the small mammal fauna across the NOK, with Theda Station lying within a transition zone between the high rainfall rugged coastal and near-coastal areas and the lower rainfall areas of the east.

3.3 Introduction

The mammal fauna of the Northern Kimberley (NOK) bioregion is sparsely documented. Most of the fauna surveys within this region have been undertaken in three national parks (Start *et al.* 2007; Corey *et al.* 2013): Mitchell River National Park (Kitchener *et al.* 1981; Bradley *et al.* 1987), Prince Regent National Park (McKenzie *et al.* 1975a) and Drysdale River National Park (McKenzie *et al.* 1975b). There have also been targeted surveys of rainforests (Friend *et al.* 1991) and islands (Gibson and McKenzie 2012), as well as some limited camera surveys (Turpin 2015). Twenty-seven species of small terrestrial mammals (defined in this study as non-volant species weighing <2 kg) are currently known to occur in the NOK (Van Dyck and Strahan 2008). While no known extinctions have been recorded in this region to date, there have been marked declines and local extinctions of several small mammal species across northern Australia (Woinarski *et al.* 2011a).

The NOK physiography is variable and largely determined by the underlying geological structure and lithology (Brocx and Semeniuk 2011). There is a rainfall gradient with higher annual rainfall towards the northwest coast (Bureau of Meteorology 2015a). These areas also tend to be more physically complex (Radford *et al.* 2014). The NOK has high species diversity and endemism but this is particularly the case for the rugged and deeply dissected uplands of the northwest (McKenzie *et al.* 2009; Doughty 2011; Oliver *et al.* 2012; Maslin *et al.* 2013). The combination of moisture gradient, topography and soil types are thought to influence landscape productivity (Stoneman *et al.* 1991; Pepper and Keogh 2014; Radford *et al.* 2014). As such, small mammals are more species diverse in the higher rainfall northwest (Start *et al.* 2007; Olds *et al.* 2016b [Chapter 2]). For instance, of the 27 currently recognised small mammal species in the NOK, 24 species have been found in the northwestern Mitchell River National Park (Bradley *et al.* 1987), whilst only 10 species have been found in the eastern Drysdale River National Park (McKenzie *et al.* 1975b; Kitchener and Vicker 1981). Two pastoral leases, Doongan and Theda Stations, occupy an extensive strip of country between the east and west NOK which, until recently, had not been surveyed for small mammals (Olds *et al.* 2016b [Chapter 2]).

The recent study undertaken on Doongan Station showed a consistently low trap success rate for small mammals (<5%) (Olds *et al.* 2016b [Chapter 2]). This was much lower than that recently recorded to the northwest (~10%) (Corey *et al.* 2013; Olds *et al.* 2016b [Chapter 2]). The lack of historical records for Doongan Station precluded determination as to whether this low trap success was indicative of decline, or if the sites had consistently supported a lower mammal abundance than that of the nearby national parks (Olds *et al.* 2016b [Chapter 2]). Nevertheless, the disparity between the small mammal records on Doongan Station, compared to those from nearby national parks, suggests that the faunal records from the national parks, particularly those to the north-west, are not indicative of small mammal diversity and abundance more broadly in the NOK.

Despite employing a considerable survey effort, a number of species known to occur in the NOK were not detected on Doongan Station (Olds *et al.* 2016b [Chapter 2]). These included species considered to be undergoing decline in northern Australia (*Isoodon auratus*, *Conilurus penicillatus*, *Mesembriomys gouldii* and *Mesembriomys macrourus* (Woinarski *et al.* 2014), specialised and/or rock-dwelling species (*Zyzomys woodwardi*, *Wyulda squamicaudata*, *Petrogale concinna*, *Petrogale burbidgei* and *Pseudomys johnsoni*), and four dasyurid species (*Phascogale tapoatafa*, *Pseudantechinus ningbing*, *Sminthopsis butleri and Sminthopsis macroura*). Furthermore, there were few individuals recorded of some species (*Melomys burtoni*, *Hydromys chrysogaster*, *Dasyurus hallucatus*, *Planigale maculata, Isoodon macrourus*, *Petropseudes dahli* and *Petaurus breviceps*), whilst two little known species were obtained (*Leggadina lakedownensis* and *Sminthopsis virginiae*) (Kutt and Kemp 2005; Woolley 2008c; Olds *et al.* 2016b [Chapter 2]). Several small mammal species considered to be common in the NOK (*Pseudomys nanus*, *Pseudomys delicatulus*, *Rattus tunneyi* and *Zyzomys argurus*) were also detected on Doongan Station. The findings for Doongan Station highlight the need for more information regarding the presence of small mammals within the NOK, particularly in savanna woodland habitats (Olds *et al.* 2016b [Chapter 2]).

The aim of this study was to further address the paucity of baseline information for the small mammal fauna of the NOK. Specifically the aims were to: (1) determine which species of small mammals occur on Theda Station and (2) compare these findings to those on adjacent Doongan Station.

3.4 Methods

3.4.1 Study area

This study was conducted on Theda Station, an area of approximately 3,250 km^2, in the NOK, Western Australia (Figure 8). Theda Station is bounded by Doongan Station to the south and adjoins Drysdale River National Park (corresponding with the Carson River) to the east. The King Edward River defines the northern and western boundaries with a section of the Morgan River forming the major watercourse through the station. The station lies within the Mitchell subregion of the NOK bioregion (Thackway and Cresswell 1995; Interim Biogeographic Regionalisation for Australia (IBRA7) 2015). Annual average rainfall is between 1000 and 1600 mm, with most rainfall occurring during the ‘wet’ season between October and April. Average maximum temperatures range from 25 to 35 °C with high humidity during the wet season (Bureau of Meteorology 2015b). Rainfall during both the wet and dry seasons varied across the study period (Figure 9).

Theda Station is a pastoral lease with free-roaming cattle (*Bos taurus*). Some cattle were removed from the station on an annual basis. Since 2008, Theda Station has been part of EcoFire, a collaborative early dry season prescribed burning program (Legge *et al.* 2011b). Fire scars show 50-60% of Theda Station was burnt each year (Figure 9), with the majority of the station experiencing a late dry season burn at least once, and up to six times, during the study period (Northern Australia Fire Information, http://www.firenorth.org.au). Theda Station is under the same land management practices as the co-owned Doongan Station (3,400km^2, Figure 8).

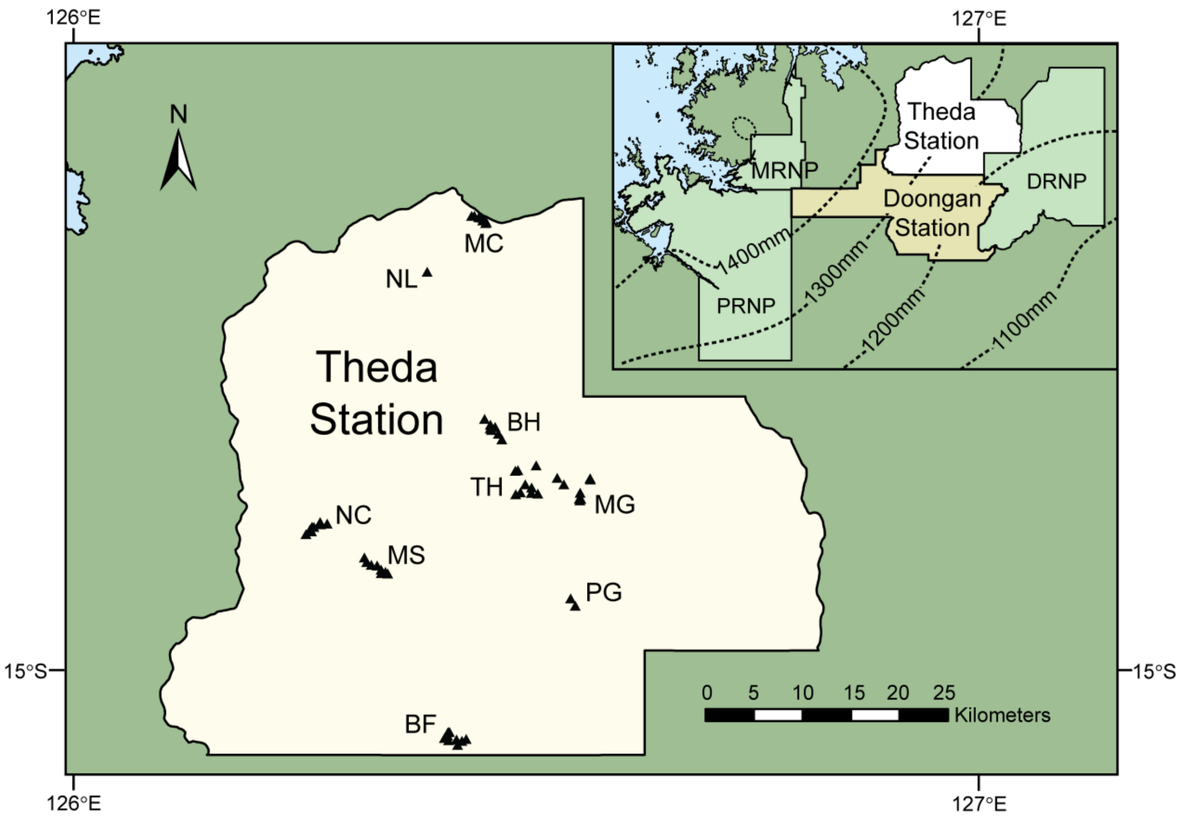

Figure 8. The study area, Theda Station and inset, its geographic location in relation to Doongan Station and three major national parks in the Northern Kimberley bioregion, Western Australia.

DRNP, Drysdale River National Park; MRNP, Mitchell River National Park; PRNP, Prince Regent National Park. See Table 9 for location codes and their co-ordinates.

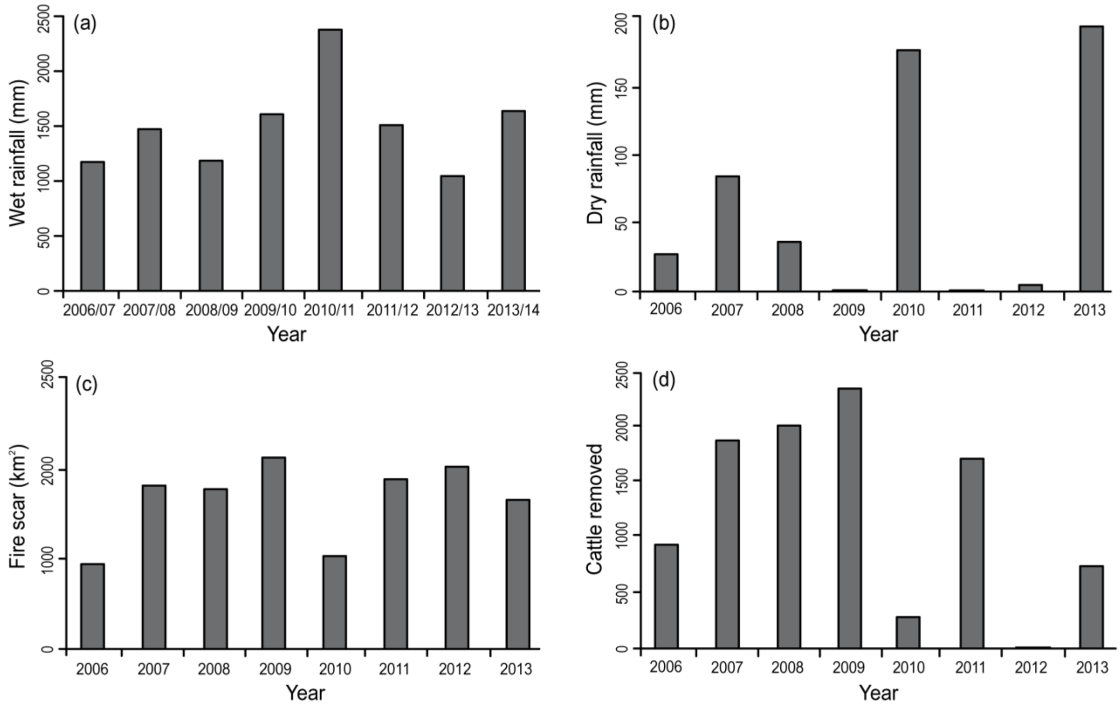

Figure 9. Rainfall during the wet and dry seasons, fire scars and cattle removed on Theda Station from 2006 to 2013.

Wet rainfall = rainfall occurring during October to April (BOM); Dry rainfall = rainfall occurring during May to September (Bureau of Meteorology 2015b). Cattle removed numbers are approximate.

3.4.2 Survey methods

Sampling of small mammals was undertaken across nine locations (Table 9; Figure 8). In total, 11 sampling periods were undertaken across nine years (2006 – 2014) (Table 10). Sites at each location were surveyed several times but in different years. Hence, in total, 226 site surveys were undertaken across 69 sites (Table 9).

Sites targeted the different habitat types at each location and were visually selected based upon landform and dominant vegetation. Eleven broad habitat types were identified and were consistent with those previously described for Doongan Station (Olds *et al.* 2016b [Chapter 2]). Trapping effort conducted within each broad habitat type is given in Table 11. Different habitat types were present at each location (Table 9) and different combinations of locations, corresponding sites, and habitats, were sampled each year (Table 10). Most locations were sampled at least every second year.

Trapping methods were similar to those described previously (Olds *et al.* 2016b [Chapter 2]). Medium 'Elliott' (10 x 10 x 33 cm) and wire treadle-style cage traps (20 x 20 x 56 cm) were baited with a mixture of peanut-paste, rolled oats and honey. Traps were opened each afternoon, checked the following morning and closed during the day. Pitfall traps were set at a depth of 50 cm in the centre of a 10 m x 30 cm drift fence. Funnel traps were placed on either side of each drift fence and protected from the sun with reflective foil insulation.

In 2006 and 2007, site surveys used a transect method (n=27 transects), with a combination of Elliott, cage and pitfall traps. Traps were placed 20 m apart along a linear transect (ranging from 10 to 40 traps per transect) and opened for three to six nights. From 2008 to 2014, a quadrat method was used (n=199 quadrats) (Woinarski *et al.* 1999a; NRETAS 2011; Olds *et al.* 2016b [Chapter 2]). The quadrat perimeter (50 x 50 m, or 80 x 20 m for riparian sites) was lined with 20 Elliott traps spaced at 10m intervals, along with a cage trap at each of the four corners. Four drift fences were placed diagonally across the quadrats, with each fence servicing one pitfall (terrain permitting) and two funnel traps. Each trap was opened for four nights per site survey. Spotlight surveys were performed by active nocturnal searching on foot. Diurnal searching was also conducted although this was targeted at herpetological species as part of a larger biodiversity study.

3.4.3 Captured animals

Captured mammals were released at the site of capture. Ear tissue biopsies were taken from captured mammals for use in future genetic studies. In 2014, where a biopsy was not collected, hair on the upper thigh region was clipped in order to identify animals that were recaptured. Recaptured animals were excluded from any of the results. Specimens of some rodent species were also collected (held at the South Australian Museum). *Pseudomys delicatulus,* as currently described, has two markedly different forms across its distribution and identifiable by sperm morphology (see Breed and Ford (2007)). Hence, the spermatozoon of an adult male was examined using Nomarski Differential Interference Contrast microscopy to determine species identity (Breed 2000). Nomenclature of all species follows Van Dyck and Strahan (2008).

3.4.4 Comparison to Doongan Station

The results on Theda Station are compared to those of a concurrent study carried out on Doongan Station, using similar trapping methods (Figure 8) (Olds *et al.* 2016b [Chapter 2]). The presence and relative abundance of each species is compared between stations using only capture records from 2008 – 2014 as the site survey methods were comparable throughout that period. Spotlight data were excluded from the comparison due to too few small mammals being recorded.

Eleven of the 14 habitat types identified on Doongan Station (Olds *et al.* 2016b [Chapter 2]) were also surveyed on Theda Station. No broad habitat types were identified on Theda Station that had not been previously found and surveyed on Doongan Station. Three habitats surveyed on Doongan Station, those of laterite flats, laterite volcanic hills and monsoon forests, were not surveyed on Theda Station. Trapping effort varied annually within the different broad habitats on both stations. Comparison of the yearly efforts from 2008 onwards on both stations is summarised in Appendix 2.

The proportion of all successful trap nights, for all species combined, is compared using Chi-square analysis. The trap success (%) per site survey is compared using the Wilcoxon rank sum test (two-sided). These two tests are also used to compare trapping periods (years) between the two stations. Finally, Chi-square analysis (two-tailed Fishers Exact Test where expected abundance was <5) is used to compare the proportion of successful trap nights for each species, and the Wilcoxon rank sum test (two-sided) is used to test for differences in the species' trap success per site survey.

Table 9. Coordinates of locations and the number of sites, number of site surveys and habitat types at each location on Theda Station, Northern Kimberley.

Habitats types: blacksoil (BlS), laterite flats (LaF), rainforest (RaF), rugged sandstone (RuS), sandstone outcrop (SaO), sandstone plains (SaP), sandstone riparian formation (SaC), volcanic hills (VoH), volcanic low woodland (VoW), volcanic riparian formation (VoR) and wetland (WeL). See Appendix 1.

Location Code	Location	Latitude	Longitude	Sites	Surveys	Habitat Types
BF	Billy Fire Flat	15˚03'S	126˚25'E	9	33	SaO, SaP, SaC, WeL
BH	Basalt Hills	14˚44'S	126˚28'E	8	34	VoH, VoW, VoR
MC	Mongonai Creek	14˚31'S	126˚27'E	8	16	RuS, SaP
MG	Morgan River	14˚48'S	126˚33'E	9	23	RaF, RuS, SaO, SaP, SaC, WeL
MS	Mud Springs	14˚52'S	126˚21'E	8	23	BlS, LaF, SaO, WeL
NC	Ngoollalah creek	14˚50'S	126˚17'E	8	26	LaF, SaO, SaP, SaC
NL	Noolawayoo	14˚34'S	126˚23'E	1	2	RuS
PG	Pangoor	14˚54'S	126˚33'E	2	2	RuS
TH	Theda Homestead	14˚47'S	126˚30'E	16	67	BlS, RuS, SaP, SaC, VoH, WeL
	Total			69	226	

Table 10. Survey effort each year from 2006 to 2014 on Theda Station.

Locations include Billy Fire Flat (BF), Basalt Hills (BH), Mongonai Creek (MC), Morgan River (MG), Mud Springs (MS), Ngoollalah Creek (NC), Noolawayoo (NL), Pangoor (PG) and Theda Homestead (TH).

			Trap Nights					Locations
Year	Period	Season	Elliott	Cage	Pitfall	Funnel	Spotlight Minutes	
2006	July - August	Dry	1140	310	0	0	840	MG, TH
2006	December	Wet	250	100	0	0	60	TH
2007	February	Wet	642	250	176	0	250	NL, PG, TH
2007	June - July	Dry	1642	428	69	0	1485	NL, PG, ST, TH
2008	April-May	Dry	2200	980	164	0	820	BH, MC, MG, TH, MS
2009	May - June	Dry	1280	256	188	512	320	BF, NC
2010	May-June	Dry	1840	368	248	736	460	BF, BH, MG, TH, NC, TH
2011	May	Dry	2400	480	296	952	600	BH, MC, TH, NC, TH
2012	May-June	Dry	2720	536	360	1088	680	BF, MG, MS, ST, TH
2013	May-June	Dry	2560	512	396	1024	640	BH, MC, MS, NC
2014	June	Dry	2720	544	428	1088	680	BF, BH, MG, ST, TH
Total			19394	4764	2325	5400	6835	

Table 11. Survey effort conducted in the 11 broad habitat types on Theda Station including the number of locations, sites, and number of site surveys.

Broad habitat types defined as per Olds *et al.* (2016b [Chapter 2]).

				Trap Nights				Spotlight Minutes
Broad habitat type	Locations	Sites	Surveys	Elliott	Cage	Pitfall	Funnel	
Blacksoil (BlS)	2	3	11	848	228	152	224	330
Laterite flats (LaF)	2	4	12	912	240	176	288	240
Rainforest (RaF)	2	1	3	556	112	24	64	40
Rugged sandstone (RuS)	5	17	51	5678	1486	341	952	3000
Sandstone outcrop (SaO)	4	8	28	2192	488	312	800	560
Sandstone plains (SaP)	5	13	38	3024	648	592	992	740
Sandstone riparian formation (SaC)	5	8	23	1620	410	200	608	380
Volcanic hills (VoH)	2	6	22	1600	416	160	512	580
Volcanic low woodland (VoW)	1	2	8	608	160	96	192	240
Volcanic riparian formation (VoR)	1	2	10	768	192	132	256	280
Wetland (WeL)	4	5	20	1588	384	140	512	445
Total		69	226	19394	4764	2325	5400	6835

3.5 Results

3.5.1 Theda Station

A total of 866 small native mammals were recorded between 2006 and 2014 (Table 12). Thirteen species from five families were found on Theda Station. No introduced rodents (i.e. *Mus musculus* or *Rattus rattus*) were detected. The total number of records for each species, together with the number of locations, sites and site surveys during which they were recorded are shown in Table 12. Critical weight range (CWR; 35-5500 g) (Burbidge and McKenzie 1989) species accounted for nine of the 13 species with four species being below the CWR (Table 12).

Elliott traps (3.4 captures per 100 trap nights) were the most successful type of trap, followed by pitfall traps (2.6 captures per 100 trap nights) and cage traps (1.7 captures per 100 trap nights). Spotlight surveys yielded 50 records, equating to one small mammal observed approximately every 135 minutes. However, 44% of these were detected in 2013 (n=22) when only 9.4% of the spotlight effort took place. Two individuals were recorded in funnel traps (*P. delicatulus* and *P. nanus*), although there was evidence that other rodents had chewed their way out of some of the funnel traps. Two *P. delicatulus*, two *P. nanus*, one *L. lakedownensis*, one *P. maculata* and two *S. virginiae* were excluded from the trap success calculations because their method of capture was not recorded, as was one hand captured *R. tunneyi* that was recorded opportunistically outside of the described trapping protocol. Results from spotlight surveys and funnel traps were excluded from further analyses due to the inconsistency and scarcity of the records obtained using these methods.

Trap success differed across the 11 trapping periods (Table 13). The lowest success occurred in February 2007. Trap success increased annually between 2009 (0.53 captures per 100 trap nights) and 2013 (8.49 captures per 100 trap nights). The highest species richness was also observed in 2013 when every species found to occur on Theda Station, except *H. chrysogaster*, was recorded (Table 13).

Table 12. Small mammals recorded between 2006 and 2014 on Theda Station.

[1] indicates an additional record not within survey effort. + denotes critical weight range species.

Species	Locations (n=9)	Sites (n=69)	Surveys (n=226)	Individuals
Muridae (Murinae)				
Leggadina lakedownensis	4	6	6	6
Pseudomys delicatulus	5	13	18	25
Pseudomys nanus+	6	26	47	135
Rattus tunneyi+	7	36	74	319[1]
Zyzomys argurus+	7	18	29	136
Hydromys chrysogaster+	2	2	3	4
Rodent sp.	-	-	-	15
Dasyuridae				
Planigale maculata	7	8	8	9
Pseudantechinus ningbing	4	11	13	16
Sminthopsis virginiae+	6	24	46	125
Dasyurus hallucatus+	1	7	9	12
Peramelidae				
Isoodon macrourus+	6	16	24	45
Pseudocheiridae				
Petropseudes dahli+	4	7	7	16
Petauridae				
Petaurus breviceps+	3	3	3	3
Total				866[1]

Table 13. Trap success (%) for small mammals on Theda Station from 2006 to 2014.

'-' denotes no records.

Species	2006 (Jul)	2006 (Dec)	2007 (Feb)	2007 (Jul)	2008 (Apr)	2009 (May)	2010 (May)	2011 (May)	2012 (May)	2013 (May)	2014 (Jun)
Muridae (Murinae)											
Leggadina lakedownensis	-	-	-	0.05	0.03	-	-	-	0.03	0.03	-
Pseudomys delicatulus	-	-	-	-	-	0.23	0.12	0.03	0.11	0.14	0.11
Pseudomys nanus	-	-	-	0.61	0.21	0.06	0.29	0.16	0.61	1.93	0.27
Rattus tunneyi	-	-	-	0.19	0.15	0.12	0.33	0.69	1.11	3.84	2.57
Zyzomys argurus	2.41	1.14	0.28	1.64	0.39	0.06	-	0.04	0.30	0.52	0.14
Hydromys chrysogaster	-	-	-	-	-	-	0.08	-	0.03	-	-
Rodent sp.	0.07	-	-	0.14	-	-	0.12	0.19	0.06	-	-
Dasyuridae											
Planigale maculata.	-	-	0.18	-	-	-	0.04	-	-	0.06	0.05
Pseudantechinus ningbing	0.07	-	-	0.23	0.03	-	0.08	0.09	-	0.03	0.03
Sminthopsis virginiae	-	-	-	-	-	0.06	0.16	0.44	0.77	1.30	0.76
Dasyurus hallucatus	-	-	-	-	0.03	-	-	0.03	-	0.29	-
Peramelidae											
Isoodon macrourus	-	-	-	-	0.06	-	-	-	0.30	0.35	0.43
Total	2.55	1.14	0.46	2.86	0.90	0.53	1.22	1.67	3.32	8.49	4.36
Site survey mean ± s.e.	n.a.	n.a.	n.a.	n.a.	0.69 ± 0.19	0.59 ± 0.19	1.25 ± 0.40	1.82 ± 0.55	3.40 ± 0.71	9.16 ± 1.48	4.55 ± 0.98

Table 14. Number of sites in the 11 broad habitats where small mammal species were detected on Theda Station.

See Table 9 for habitat abbreviations and for total number of sites at which each broad habitat type occurred. Broad habitat types are defined in Olds *et al*. (2016b [Chapter 2]). Total Habitats indicates the number of different habitats in which species were observed.

Species	BlS	LaF	RaF	RuS	SaO	SaP	SaC	VoH	VoW	VoR	WeL	Total Habitats
Muridae (Murinae)												
Leggadina lakedownensis	1	1	1		1				1		1	6
Pseudomys delicatulus		1			3	7	2					4
Pseudomys nanus	3	4	1	1	1	2	3	4	2	2	3	11
Rattus tunneyi	3	2	1	2	4	7	4	4	2	2	5	11
Zyzomys argurus				14	3							2
Hydromys chrysogaster				1							1	2
Rodent sp.	1		1	1	1		1	2				5
Dasyuridae												
Planigale maculata	1	1		1	1		1	1			2	7
Pseudantechinus ningbing				10			1					2
Sminthopsis virginiae	3	1	1		1		4	5	2	2	5	9
Dasyurus hallucatus				4		3						2
Peramelidae												
Isoodon macrourus	2	3	1	1			1	3	2	2	1	9
Pseudocheiridae												
Petropseudes dahli[+]				2								1
Petauridae												
Petaurus breviceps[+]				1		1			1			3

3.5.2 Muridae

Rattus tunneyi was both the most widely, and most frequently recorded small mammal species (Table 12). It was not found prior to July 2007, but it was detected in every trapping period thereafter and in all broad habitat types (Table 14). Trap success markedly increased in 2013, when basalt sites yielded 105 individuals with between 8 and 19 individuals per site survey (between 7% and 17% trap success). These accounted for 74% of *R. tunneyi* records for that trapping period. Surveys of these sites also yielded comparatively high abundances in 2014 with 50 individuals being recorded on basalt sites, including one site with 20 individuals. *Rattus tunneyi* was also found to be high in relative abundance on blacksoils, including one site that yielded 17 and 15 individuals during site surveys in 2012 and 2014 respectively.

Two species of *Pseudomys* were captured. *Pseudomys nanus* was captured frequently (Table 12) and within all broad habitat types (Table 14), with the greatest number being obtained from a rainforest patch site where 13 individuals were recorded.

Only 25 *Pseudomys delicatulus* individuals were captured (Table 12). This species was not detected until 2009 (Table 13). Light microscopy of sperm morphology from one individual showed a highly variable, but generally pear-shaped, head morphology with the tail attached off-centre or mid-basally, mean total tail length of 86µm (n=20) and midpiece length of 23 µm.

The greatest number of individuals of any species detected during a site survey was 34 *Z. argurus* in 2006. This species was predominately detected on rugged sandstone and outcrops (Table 14). The only *Z. argurus* individuals not recorded on sandstone (n=2) were captured on a volcanic hill site.

Two other rodent species were rarely captured. These included six *L. lakedownensis* individuals (Table 12), which were predominantly on deep sandy-loam soils, although all were from different broad habitat types (Table 14). *Hydromys chrysogaster* was the least frequently recorded rodent species (n=4). Three individuals were captured at one wetland site: one adult female and a juvenile male in 2010, and a single adult male at the same site in 2012.

3.5.3 Dasyuridae

Sminthopsis virginiae was the most widely detected dasyurid species. One hundred and twenty-five individuals were recorded across most broad habitat types (Table 14). Sixty-five individuals were captured at the same location on volcanics across multiple years (2011, 2013 and 2014). This species was predominantly captured on deep soils of sandy-clay, red clay and cracking blacksoils, with dense grasses.

Sixteen *Pseudantechinus ningbing* were captured at four locations (Table 12) all of which were in sandstone habitats (Table 14). Similarly, *Dasyurus hallucatus* was only detected within sandstone habitats (Table 14) but only at one location. Ten of the 12 individuals were recorded in 2013. *Planigale maculata* was the least frequently detected dasyurid with nine individuals being broadly distributed across seven locations (Table 12), each in a different habitat type (Table 14).

3.5.4 Peramelidae

Isoodon macrourus was found in all broad habitat types, except for sandstone outcrops and sandstone plains (Tables 12 - 14). Eleven of these individuals were detected at one structurally complex rainforest during site surveys in 2012 (n=6) and 2014 (n=5), whilst nineteen individuals were recorded on volcanics during site surveys in 2013 (n=8) and in 2014 (n=11).

3.5.5 Pseudocheiridae

Petropseudes dahli was the only possum species recorded and it was only detected during spotlight efforts. All 16 records (Table 12) were from within rugged sandstone (Table 14).

3.5.6 Petauridae

Petaurus breviceps was only recorded during spotlight efforts at three sites (Table 12), all of which were in different habitat types (Table 14).

3.5.7 Comparison of Theda and Doongan Stations

Twelve of the small mammal species detected on Theda Station were also recorded on the adjacent Doongan Station. These include six species of rodent, three species of dasyurid, *I. macrourus*, *P. dahli* and *P. breviceps* (Table 15). *Pseudantechinus ningbing* was the only species found on Theda Station that had not been recorded on Doongan Station. Conversely, *M. burtoni* was not detected on Theda Station but was recorded on Doongan Station (Table 15). Comparison of species occurrence by broad habitat type showed similar patterns across the two stations (Table 15). However, *P. nanus* was recorded in two habitat types on Theda Station (blacksoil and volcanic hills) in which it was not detected on Doongan Station. Similarly, *I. macrourus* was recorded in a greater diversity of habitats on Theda Station. *Rattus tunneyi* was recorded in all habitat types surveyed across both stations, whilst *S. virginiae* was recorded in all habitats except for rugged sandstone.

Trap success (2008-2014) on Theda Station was significantly higher than on Doongan Station (χ^2 = 52.52, p <0.001) (Table 17). However, there was no significant difference in trap success across site surveys (*U*=19349, p=0.183). This indicates that the total proportion of successful trap nights was not consistently higher across all the sites on Theda Station, that is, a higher trap success occurred during only some of the site surveys.

Mean trap success for both Theda and Doongan Stations was low (<1%) in 2008 and 2009, peaked in 2013 and decreased in 2014 (Figure 10). Mean trap success was lower on Theda Station than on Doongan Station in 2009, 2010 and 2011 but differences were not statistically significant (Table 16; Figure 10). Trap success was significantly higher for Theda than Doongan Station in 2008 (χ^2 = 8.756, *p*=0.003) but there was no significant difference in trap success across site surveys (*U* = 472, *p* = 0.053; Table 16). A similar pattern was observed in 2012 (χ^2 = 11.984, $p \leq 0.001$; *U* = 580, *p*= 0.145; Tables 16 and 17).

Trap success differed significantly between stations for three species: *L. lakedownensis* was captured more frequently on Doongan Station, whilst *R. tunneyi* and *I. macrourus* were captured more frequently on Theda Station (Table 17). Total captures of *P. nanus* were significantly higher on Theda than on Doongan Station (χ^2 = 6.861, *p*=0.008), but the Wilcoxon test did not indicate a significant difference (*U* = 19688, *p*= 0.150). The converse was found for *P. delicatulus*, with a higher trap success on Doongan (χ^2 = 9.591, *p*=0.001; *U* = 22009, *p*= 0.095). There were no other significant differences (Table 17).

Table 15. Comparison of species occurrence in broad habitat types on Theda and Doongan Stations.

See Table 11 for abbreviations. Broad habitat types defined in Olds *et al.* (2016b [Chapter 2]). Black shading – species detected both stations; dark grey – species detected on Theda Station only; light grey – species detected on Doongan Station only; white – species not detected on either station. + indicates habitats not surveyed on Theda Station. *Petropseudes dahli* and *Petaurus breviceps* occur on Doongan Station but were recorded outside site surveys.

Species	BlS	LaF	RaF	RuS	SaO	SaP	SaC	VoH	VoW	VoR	WeL	LaV+	LaC+	MoF+
Muridae (Murinae)														
Leggadina lakedownensis	Black	Black	Dark grey		Black	Light grey			Dark grey		Black	Light grey	Light grey	
Pseudomys delicatulus	Light grey	Black		Light grey	Black	Black	Black				Light grey	Light grey	Light grey	
Pseudomys nanus	Dark grey	Black	Black	Black	Black	Black	Black	Dark grey	Black	Black	Black	Light grey	Light grey	Light grey
Melomys burtoni			Light grey											
Rattus tunneyi	Dark grey	Dark grey	Black	Black	Black	Black	Black	Black	Black	Black	Black	Light grey	Light grey	
Zyzomys argurus				Black	Black	Light grey	Light grey	Light grey		Light grey	Light grey			Light grey
Hydromys chrysogaster			Light grey	Black							Dark grey			
Dasyuridae														
Planigale maculata	Dark grey	Dark grey		Dark grey	Dark grey	Light grey	Black	Dark grey			Dark grey	Light grey	Light grey	Light grey
Pseudantechinus ningbing				Dark grey			Dark grey							
Sminthopsis virginiae	Black	Dark grey	Black		Dark grey	Light grey	Black	Dark grey	Black	Dark grey	Black	Light grey	Light grey	
Dasyurus hallucatus				Dark grey		Black	Light grey							
Peramelidae														
Isoodon macrourus	Dark grey	Dark grey	Black	Dark grey		Light grey	Dark grey	Dark grey	Black	Dark grey	Black			
Pseudocheiridae														
Petropseudes dahli				Dark grey										
Petauridae														
Petaurus breviceps				Dark grey		Dark grey			Dark grey					

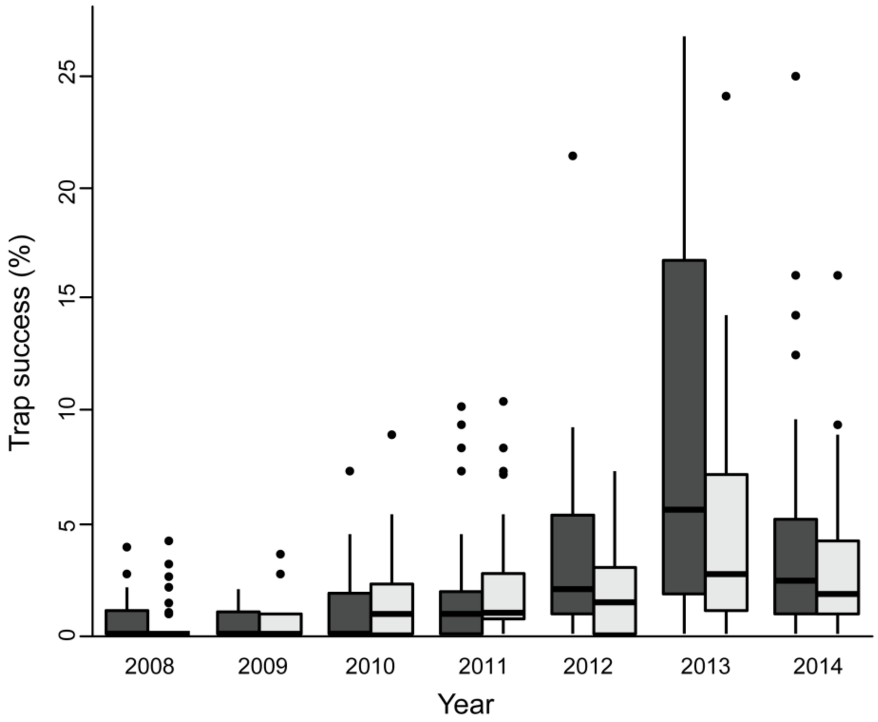

Figure 10. Box and whisker plot of mean trap success rates for Theda Station (dark grey) and Doongan Station (light grey) from 2008 to 2014.

Columns show mean trap success per site.

Table 16. Comparison of trap success by year on Theda Station and Doongan Station between 2008 and 2014.

Chi-squared comparison of total captures = χ^2 and P; Wilcoxon comparison of capture rate per site survey = U and p. * denotes significance <0.05 and ** <0.01

Year	χ^2	*P*	*U*	*p*
2008	8.7560	0.003**	448	0.042*
2009	0.3392	0.560	132	0.866
2010	1.2638	0.261	309	0.463
2011	0.2854	0.593	580	0.145
2012	12.421	<0.001**	434	0.153
2013	35.924	<0.001**	369	0.036*
2014	11.521	<0.001**	486	0.348
Total	52.52	<0.001**	19349	0.183

Table 17. Comparison of trap success by species on Theda Station and Doongan Station between 2008 and 2014.

Chi-squared comparison of total captures = χ^2 and P; Wilcoxon comparison of capture rate per survey per site = U and p. * denotes <0.05 and ** <0.01.

Species	χ^2	*P*	*U*	*p*
Total captures	52.52	<0.001**	18724	0.0908
Muridae (Murinae)				
Leggadina lakedownensis	5.709	0.017*	21736	0.021*
Pseudomys delicatulus	9.591	0.002**	21672	0.141
Pseudomys nanus	6.861	0.008**	1.9457	0.142
Rattus tunneyi	70.84	<0.001**	18210	0.010*
Zyzomys argurus	0.025	0.8754	2.0672	0.983
Hydromys chrysogaster	0.001	0.683	2.0470	0.289
Dasyuridae				
Planigale maculata	0.159	0.501	2.0549	0.683
Sminthopsis virginiae	0.097	0.756	1.9804	0.300
Dasyurus hallucatus	8.018	0.004*	1.9841	0.008*
Peramelidae				
Isoodon macrourus	25.722	<0.001**	1.8559	<0.001**

3.6 Discussion

This study is the first survey of the small mammal fauna on Theda Station. Thirteen of the 27 small mammal species known to occur in the NOK were detected. This study establishes baseline data on the presence of small mammals on Theda Station, and provides further information on the current distribution of these species.

The rodent species considered common on Doongan Station (*P. delicatulus*, *P. nanus*, *R. tunneyi* and *Z. argurus*) (Olds *et al.* 2016b [Chapter 2]), were recorded frequently. Although *P. delicatulus* is widespread in northern Australia (Ford 2006), there is currently some taxonomic conjecture. The *P. delicatulus* spermatozoa from Theda Station was found to be similar to that of other individuals in most of the top end of the Northern Territory and northwest WA (Breed 2000). Those from Queensland and Groote Eylandt show far less morphological variability (Breed 2000); Thalli Moya-Smith and Bill Breed unpublished observations). These observations suggest that the animals in the western part of the range of *P. delicatulus*, including those obtained in the current study, are a separate species from those occurring in eastern Australia and on Groote Eylandt. The variability of their sperm head and comparatively short sperm tail suggests that this species has a monogamous breeding system (Calhim *et al.* 2007; van der Horst and Maree 2014; Varea-Sánchez *et al.* 2014) and emphasises the need for the taxonomy of this species complex to be resolved.

Similar to findings on Doongan Station (Olds *et al.* 2016b [Chapter 2]), *S. virginiae* was the most frequently detected dasyurid on Theda Station. Published records of this species from the NOK are scarce despite it being considered common in this region (Woolley 2008c). Theda and Doongan Stations together provide the most numerous records of *S. virginiae* in the NOK. Ground refuge is thought to be important for *S. virginiae* as it has been detected from sites with a dense grass layer and/or ground cover, such as *Pandanus* spp. leaves (Braithwaite and Lonsdale 1987; Firth *et al.* 2006). Further investigation of the condition of ground cover is being undertaken in relation to *S. virginiae* presence. The results may indicate the reasons for their frequent detection on both stations.

Pseudantechinus ningbing occurs throughout the NOK and has predominantly been recorded in rocky sandstone habitat (McKenzie *et al.* 1975a; Legge *et al.* 2008; Woolley 2008b). Our findings are consistent with these observations. Trapping effort in rugged sandstone and sandstone outcrops was marginally greater on Theda Station which may explain why it was recorded there and not on Doongan Station. This may also explain why *P. dahli* and *D. hallucatus* were detected more frequently on Theda Station. These are both primarily rock-dwelling species, although *D. hallucatus* is found in a range of habitats (Webb *et al.* 2008; Hill and Ward 2010).

Dasyurus hallucatus is locally common at near-coastal and island sites in the NOK (Gibson and McKenzie 2012; Woinarski *et al.* 2014). Although more frequently recorded on Theda than on Doongan Station, records were still few, despite extensive trapping in rugged sandstone country, which is their preferred habitat (Hill and Ward 2010). This finding, together with the few records on Doongan Station and lack of detection in the Drysdale River National Park (Start *et al.* 2007), suggests that *D. hallucatus* may no longer be as widespread in the NOK as previously suggested (Woinarski *et al.* 2014). Historically, its range is known to have extended across northern Australia, although the eastern

(Woinarski 1992b) and southwestern Kimberley (Start *et al.* 2007; Woinarski *et al.* 2014) populations have recently declined and *D. hallucatus* is now considered to have a discontinuous distribution across northern Australia (Hill and Ward 2010).

The low detection rate of *H. chrysogaster* is likely to be a result of our survey design. It occurs in close proximity to water, and predominantly inhabits and forages in both riparian vegetation and in the water (Olsen 2008). Our trapping effort was likely to be on the periphery of its favoured streamside habitat. *Hydromys chrysogaster* is primarily a carnivore (Olsen 2008). It is rarely trapped using universal bait but, in Queensland, it can be captured in meat-baited traps (Laurance 1992), which we did not use. It occurs on the Drysdale River (Start *et al.* 2007) and was also found on Doongan Station (Olds *et al.* 2016b [Chapter 2]).

The low detection of *L. lakedownensis* on Theda Station may also be due to their preferred habitat not being surveyed. Whilst they are known to be elusive (Cole and Woinarski 2000), a large proportion of the individuals detected on Doongan Station were in laterite volcanic hills and along lateritic creeklines (Olds *et al.* 2016b [Chapter 2]). These habitats were not surveyed on Theda Station. Elsewhere in the NOK, they have been found in a variety of habitats, including woodlands and riparian areas with dense grass layers on stony, basalt-derived, laterite-derived and sandstone-derived soils (Bradley *et al.* 1987). Further investigation is needed to determine the reason(s) for the apparent rarity of *L. lakedownensis*.

Although *M. burtoni* is usually present in the higher-rainfall western NOK, it was also found to occur on Doongan Station (Olds *et al.* 2016b [Chapter 2]). If it is present on Theda Station, the failure to detect this species is likely due to limited trapping effort in its preferred habitat. This species tends to occur in dense rainforest within close proximity to water and in well vegetated riparian areas (Kerle 2008). Similarly, the failure to detect *P. johnsoni* may be due to limited trapping within its preferred habitat of hummock grasslands on stony hills (Kitchener and Humphreys 1986 as *Pseudomys laborifex*; Ford and Johnson 2007). *Pseudomys johnsoni* constructs mounds using pebbles and as such, generally occurs in run-off landscapes where pebbles are abundant, avoiding weathered bedrock, sand and clay substrates (Ford and Johnson 2007).

Zyzomys woodwardi is endemic to the Kimberley region but it was not detected on Theda Station. It is a specialist of highly dissected areas, inhabiting sandstone and volcanic rugged boulder country and is restricted to the northwest coast (Burbidge and McKenzie 1978; Fleming and McKenzie 1995). *Zyzomys argurus* was widespread on Theda Station and is known to inhabit lower-rainfall areas than *Z. woodwardi* and in places, replaces it (Begg 1981).

The three species of tree-rats not detected in the current study were similarly not detected on Doongan Station (Olds *et al.* 2016b [Chapter 2]). There has been significant range contraction of *M. macrurus* (Woinarski *et al.* 2014), whilst *M. gouldii* and *C. penicillatus* have always been rare in Western Australia (Firth *et al.* 2010; Woinarski *et al.* 2014). The decline of the two *Mesembriomys* species in northern Australia has been attributed to the effects of European settlement, including pastoralism and changed fire regimes (Firth *et al.* 2005; Woinarski *et al.* 2014). This has also been inferred for *C. penicillatus* (Woinarski *et al.* 2014). Recent analyses of a dingo (*Canis lupis dingo*) scat collected from Theda Station appeared to contain hairs from *Mesembriomys* or *Conilurus* species (R. Palmer pers. comm.). Thus, one or more of these species may still be present on this Station albeit at very low density. Confirmation would require targeted survey efforts.

Similarly, *I. auratus* is now rare and restricted to the Kimberley, four offshore NOK islands (Augustus, Uwins, Lachlan and Storr Islands), two islands off the Pilbara coast (Barrow and Middle Islands) and Marchinbar Island (Northern Territory) (Woinarski *et al.* 2014). Its current distribution represents a significant contraction from its pre-European distribution across arid central Australia (Palmer *et al.* 2003). Known populations of *I. auratus* occur in dissected rocky sandstone and vine thicket habitat in the NOK (Palmer *et al.* 2003) and it is likely that our surveys on Theda Station were not within suitable habitat for this species.

The presence or absence of *P. tapoatafa* on Theda Station remains unresolved. Recent range contractions have occurred in the Kimberley region (Soderquist and Rhind 2008; Radford *et al.* 2014) but they can also be difficult to detect using traditional survey methods such as Elliott and cage trapping (Traill and Coates 1993). Thus, their absence in this study is not necessarily indicative of absence for Theda Station. The absence of the two other dasyurid species was expected. *Sminthopsis butleri* is known from only one location in the NOK (Woolley 2008a). *Sminthopsis macroura* only occurs in the southern margin of the NOK (Morton and Dickman 2008).

The amount of rainfall during both the wet and the dry season varies annually in the NOK (Shi *et al.* 2008). It is thought that fauna in northern Australia is influenced by rainfall (Woinarski *et al.* 2005). Recently in the Kimberley, a positive association has been found between the amount of rainfall in the wet season prior to trapping and the combined trap success of mammals >150 g in non-rocky savannas in the high rainfall zone (>800 mm annual rainfall) (Radford *et al.* 2014). A similar pattern was observed for total trap success in both rocky and non-rocky savanna in the low rainfall zone (<600 mm), but no associations were found in the medium rainfall zone (600-800 mm) (Radford *et al.* 2014). The results from Theda Station do not appear to show a direct association with antecedent rainfall, but trap success did appear to follow rainfall pattern. For instance, the high dry season rainfall in 2010 was followed by the highest wet season rainfall during the study period, in 2010/2011 (Figure 9), but the highest trap success occurred in 2013. Although detailed investigation was beyond the scope of this paper, this suggests there may be delayed changes in small mammal abundance as a result of rainfall variation and there may be a time-lag or potentially cumulative effect of high rainfall seasons. In arid systems, increases in the densities of rodents in relation to changes in primary productivity (rainfall driven) are similarly delayed (Letnic *et al.* 2005). In the NOK, changes in small mammal populations may be less pronounced than those found in arid areas as nutrients and food resources are less limiting (Radford *et al.* 2014). Whilst the relationship between rainfall and small mammals in the NOK is not yet clear, rainfall variation likely contributed to the changes in trap success on Theda Station.

Fire history attributes including patch size, frequency, and intensity, have been found to influence mammal abundance in the NOK (Radford *et al.* 2015). Species tend to fall into two functional groups: those that prefer recently burnt habitats, such as *R. tunneyi* and *P. nanus*, and those that prefer long unburnt habitats, such as *I. macrourus* (Andersen *et al.* 2005; Firth *et al.* 2006; Legge *et al.* 2008). Additionally, there is evidence that the abundance of small mammals is reduced by both intense and high frequency fires in northern Australia (Woinarski *et al.* 2011a). The only year in which there was a notable change in the fire scar trends was a decrease in 2010, coinciding with the high rainfall, which confounds basic associations from being made here. Whilst there is evidence that fire affects small mammals, the role of fire has not yet been disentangled from other processes, and there is still considerable uncertainty as to its influence (Radford 2010; Radford 2012). Investigation of the fire history at survey sites may help elucidate this relationship.

Changes in cattle numbers on Theda Station (Figure 9) may have contributed to the changes in trap success. The carrying capacity of Theda Station is estimated at approximately 7, 500 cattle units (dry cow or steer in excess of 2 years of age) (Skroblin *et al.* 2014). This means that the cattle reduction between 2006 and 2010 was in the vicinity of 15-20% each year. This is likely to have impacted the overall cattle numbers across the station, particularly when stock was removed in consecutive years. Cattle in the NOK are free-roaming and wide-spread, and migration and breeding would be occurring, hence accurate cattle numbers are not available. Nevertheless, limited research in northern Australia has shown pastoralism may create variation in faunal assemblages, with more pronounced effects for mammal species associated with the ground and understorey (Woinarski 1999; Woinarski and Ash 2002). In the Central Kimberley, increases in both the abundance and richness of small mammals followed cattle removal (Legge *et al.* 2011a). Mammal abundance doubled after destocking a 400 km^2 fenced area, with relatively small native rodents and dasyurids demonstrating positive responses post-removal (Legge *et al.* 2011a). However, detailed understanding of how these variables influence the small mammal fauna in the NOK is impeded by inadequate baseline and temporal data. Investigation of the small mammal assemblages on Theda Station in association with site specific land condition, rainfall and fire histories, is being undertaken.

The combination of rainfall, topography and soil types, along with processes such as fire and grazing, affect landscape productivity. Terrestrial ecosystems are responsive to changes in productivity (Craig 1997; Woinarski *et al.* 2005; Devi Kanniah *et al.* 2010), and this is likely to have contributed to the changes that occurred on Theda Station across the study period. Recently, a state-and-transition model has been proposed for mammals in the Kimberley (Radford *et al.* 2014). Different states are defined according to the composition and relative abundance of small mammal species present in the community. The findings on Theda Station are, for the most part, supportive of this model. Most sites were in State 0, with low or zero trap success, particularly in the early years of the study period. State I, which is dominated by small insectivorous dasyurids in the central Australian state-and-transition model counterpart (Letnic and Dickman 2010), was excluded from the final Kimberley model as few sites (2%) in Radford *et al.*'s (2014) study represented this state.

However, the trapping success of *S. virginiae*, particularly in 2012, indicates that on Theda Station it is possible that State I was more common and may warrant inclusion in the Kimberley conceptual model, at least for non-rocky savanna. The ratios of species observed on Theda Station, along with Doongan Station, should be tested to see if this is the case. Omnivorous rodents (*P. nanus, P. delicatulus* and *R. tunneyi*) were widespread, supporting the presence of State II assemblages. The increases in trap success of rodents, along with *D. hallucatus* and *I. macrourus*, support the likely transition of some sites into State III assemblages.

It appears that improvements in the abundance of small mammals on Theda Station have occurred during this study period. This is a rare occurrence in northern Australia, a region where declines are generally being reported (Woinarski *et al.* 2001; Fitzsimons *et al.* 2010; Woinarski *et al.* 2010). Fire regimes and the prevalence of cattle and other introduced species, especially cats and cane toads, are thought to be the major causes of mammal declines in northern Australia (Fitzsimons *et al.* 2010). Whilst the absence of prior studies on Theda Station precluded long-term changes from being examined further here, the current study provides important baseline information for such future investigations, especially given the impending arrival of the cane toad, as it has already reached the NOK (but not yet Theda or Doongan Stations) (DPAW 2015a). Recent studies have also shown that feral cats (*Felis catus*) may be having a greater impact in the Kimberley region than has been recognised previously (Frank *et al.* 2014; McGregor *et al.* 2014), however, this interaction has not been considered here.

The studies on Theda and Doongan Stations provide the most extensive long-term data set for the NOK, and provide a unique opportunity to examine both the finite environmental relationships of species and the long-term changes in small mammal species' relative abundance. The prevalence of a number of species rarely detected elsewhere highlights the importance of protecting the savanna, particularly as the region is becoming more accessible for mining and tourism. Monitoring of existing sites and surveying new sites are both essential for understanding species distributions and restrictions, and ultimately for the conservation of these species.

Chapter 4
Effects of broad-scale environmental factors on small mammal community composition in the Northern Kimberley, Western Australia

Pale Field Rat
Rattus tunneyi

Effects of broad-scale environmental factors on small mammal community composition in the Northern Kimberley, Western Australia

Liberty G.M. Olds[A], Cecilia Myers[B], Graeme Hastwell[C], William Breed[D]

[A] School of Biological Sciences, University of Adelaide, Adelaide, SA, 5000, Australia

[B] Dunkeld Pastoral Company Pty Ltd, Dunkeld, Vic, 3294, Australia

[C] P.O. Box 1406 Ashton, SA, 5137, Australia

[D] School of Medicine, University of Adelaide, Adelaide, SA, 5000, Australia

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4.1 Statement of authorship

By signing the Statement of Authorship, each author certifies that their stated contribution to the publication is accurate and that permission is granted for the publication to be included in the candidate's thesis.

Liberty Olds: (Candidate) __________________________ Date:__________________

Small mammal trapping, data collection, habitat assessments, data analysis, preparation of the full manuscript including all tables and figures.

Cecilia Myers:_ Date: 17/4/16

Provided on-ground expertise, land management, field support and data collection.

Graeme Hastwell:_ Date: 2 May 2016

Provided expert advice in statistical modelling and manuscript revision.

William G Breed: _ Date: 26/4/16

Provided general support, manuscript revision and supervised the direction of the study.

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4.2 Abstract

The Northern Kimberley is one of the last bioregions in Australia where no known mammal extinctions have been recorded to date, yet the influence of environmental variation on the small mammal community composition in this region is poorly understood. Here we examined responses of the small terrestrial mammal (<2kg, non-volant) community to broad-scale environmental factors. We used data collected between 2008 and 2014, encompassing 408 site surveys across 137 sites. A relatively new tool for modelling multivariate abundance data in ecology, the *mvabund* package, is used to examine which broad-scale variables influence community structure. We found trapping method influenced the community being detected, likely due to species' differences in morphology, behaviour and ecology. Land systems, which describe recurring patterns of topography, soils and vegetation, were strongly associated with the small mammal community. We suggest that land systems may be useful as a predictor of community composition. We found community composition changed between 0 – 48 months post-fire, with the greatest species diversity between 6-24 months since fire. Contrastingly, fire frequency showed little association with small mammal community composition. Rainfall, both during the wet and dry seasons prior to trapping, also influenced small mammal community composition. The influence of antecedent wet season rainfall had a more temporal effect, with every wet season examined (up to four years prior) demonstrating a significant association. Rainfall in the dry season was only influential up to two years prior to trapping. Our results show evidence for a potential time-lag or cumulative effect of high rainfall seasons. We suggest the influence of the broad-scale variables is synergistic, and their combination likely affects landscape productivity, which in turn drives variation in community composition.

4.3 Introduction

A fundamental aspect of ecology is the identification and explanation of patterns in the distribution and abundance of species (Andrewartha and Birch 1954). Similarly, community ecology describes the factors that determine the abundance & distribution of co-occurring suites of species. Small mammal community ecology has been the focus of a number of studies, particularly of desert species in South America, Africa and Asia (Kelt

2011). Changes in small mammal communities are driven, at least in part, by changes or differences in environmental variables (Radford *et al.* 2014). In temperate coastal areas in Australia, small mammal communities are influenced by both vegetation structure and composition (Holland and Bennett 2007; Monamy and Fox 2010). In the central arid regions, rainfall is a key driving force, whilst vegetation attributes may be less influential (Dickman *et al.* 1999a; Letnic *et al.* 2004). In mallee habitats, broad-scale drivers such as rainfall are less explanatory of small mammal community changes (Kelly *et al.* 2013).

Despite the Northern Kimberley (NOK) being one of the last bioregions in Australia to have no known recent mammal extinctions (Burbidge *et al.* 2008), few studies have focused on the small mammal fauna of this region. To date, insight into the small mammal fauna in the NOK has relied heavily on studies in other parts of northern Australia (McKenzie *et al.* 2009; Radford *et al.* 2014).

Trap success rates in small mammal surveys in northern Australia are typically low, exacerbated by major declines and range contractions of many species (Woinarski *et al.* 2010; Woinarski *et al.* 2014). Both the limited research and the low mammal abundances have hindered the capacity to decipher which factors affect small mammal communities (Radford *et al.* 2015). Nevertheless, the protection afforded by dissected topography, in conjunction with high rainfall, may be a major contributor to the persistence of small mammal species in the NOK (Woinarski *et al.* 2011a; Pepper and Keogh 2014).

In north-western Australia, rainfall is thought to influence small mammal abundance and diversity, but the mechanisms and relationships are yet to be determined (Radford *et al.* 2014). Rainfall gradient has been correlated with small mammal diversity (Olds *et al.* 2016b [Chapter 2]), and a recent study of state and transition models found some association of species abundance with rainfall, particularly when considered in conjunction with the type of savanna (rocky or non-rocky) (Radford *et al.* 2014). Trap success was positively associated with rainfall in the wet season prior to trapping but only in the low rainfall zone. Similarly, the abundance of large-bodied (>150g) mammal species was positively associated with wet season rainfall, but, conversely, only in non-rocky savanna in the high rainfall zone. However, the correlation of rainfall overall with changes in the small mammal assemblage could not be clearly deciphered (Radford *et al.* 2014). Similarly, small mammal species are known to respond to fire seasonality, frequency and extent (Radford 2010), but the influence of these factors been shown to produce variable results (Legge *et al.* 2008; Radford *et al.* 2014; Radford *et al.* 2015).

The aim of this study was to determine which broad-scale environmental factors are associated with small mammal community composition in the NOK. Fluctuations in the relative abundance of small mammals were observed over a seven year period (2008 – 2014) on Doongan and Theda Stations in the NOK (Olds *et al.* 2016b [Chapter 2]; Olds *et al.* 2016b [Chapter 2]), however, the extent to which environmental factors contributed to these fluctuations could not be established due to the low trap success rate and non-normality of the data (Olds *et al.* 2016b [Chapter 2]). Mammal surveys produce count data that typically contain a large proportion of zeroes (Martin *et al.* 2005). Consequently, naively applying statistical methods intended for normally-distributed continuous data to mammal survey data will almost certainly lead to erroneous conclusions. Recent advances in statistical modelling methods enable ecologists to better understand how environmental conditions affect community responses by accounting for uncertainty and assumptions within the data, and allowing formal inferences to be made (Warton *et al.* 2015). This means that species within communities can now be examined collectively within a multivariate regression framework. This study uses these new methods to determine the factors associated with community dynamics in the NOK. Here we use these new modelling techniques to determine which factors explain the patterns of relative abundance within the small terrestrial mammal community on Doongan and Theda Stations.

4.4 Methods

4.4.1 Study region

This study was conducted in the NOK bioregion in Western Australia (Interim Biogeographic Regionalisation for Australia (IBRA7) 2015), across an area of approximately 6,550 km^2 (Figure 11). The study region encompassed two adjoining pastoral leases (free-roaming cattle, *Bos taurus*): Doongan and Theda Stations. These stations are bounded to the east by the Drysdale River National Park and to the west by the Prince Regent National Park (Figure 11). The climate is monsoonal, with most rain falling during the 'wet' season from October to April, and little precipitation in the 'dry' season from May to September (Bureau of Meteorology 2015b). There is a northwest – southeast rainfall gradient, with mean annual rainfall decreasing with increasing distance from the coast (Bureau of Meteorology 2015a). The study region encompasses the Couchman and Foster Ranges and is bounded on the east by the Carson Escarpment. Major rivers include the King Edward, Mitchell and Morgan Rivers. The geology of the area comprises mainly sandstones and volcanics (Speck *et al.* 1960). The landscape is dominated by savanna woodland but supports a variety of habitat types including grasslands (hummock and tussock), shrubland, forest, rainforests and paperbark swamps (Graham 2001a; Olds *et al.* 2016b [Chapter 2]; Olds *et al.* 2016b [Chapter 2]).

4.4.2 Study sites

This study utilises a subset of the data presented in Olds *et al.* (2016b [Chapter 2]) and Olds *et al.* (2016b [Chapter 3]). The data used here were collected during the dry seasons of 2008 – 2014, from 137 sites (Figure 11). Some of these sites were surveyed across multiple years. Data from a total of 408 site surveys were used. Sites were selected so that representatives of each of the habitat types were targeted, and that these were accessible from the camp location, with camp locations being chosen for accessibility and proximity to potable water (Olds *et al.* 2016b [Chapter 2]; Olds *et al.* 2016b [Chapter 2]).

4.4.3 Small mammal data

Trapping quadrats were similar to those used elsewhere in northern Australia (Woinarski *et al.* 1999b; NRETAS 2011) and are detailed in Olds *et al.* (2016b [Chapter 2]) and Olds *et al.* (in review [Chapter 3]). Quadrats typically comprised 20 Elliott traps (10 x 10 x 33 cm; 31, 539 total trap nights) equally spaced around a 50 x 50 m perimeter (20 x 80 m for riparian sites), and a cage (20 x 20 x 56 cm; 7524 total trap nights) and a pitfall (15 cm diameter x 50 cm deep; 4390 total trap nights) trap set in each corner. Each pitfall had a 30 cm x 10 m drift fence running diagonally across the quadrat. Traps were baited with a peanut butter and oats mixture and open for four nights, except for 9 inaccessible sites where time constraints limited sampling to 3 nights in the 2008 surveys. Some sites also differed in the number of traps employed, e.g. where bedrock prevented the use of pitfall traps. In total, 1120 records from eight small mammal species were included in the analyses (Table 18). Species with too few records (*Hydromys chrysogaster, Planigale maculata* and *Pseudantechinus ningbing*) were excluded from the analyses.

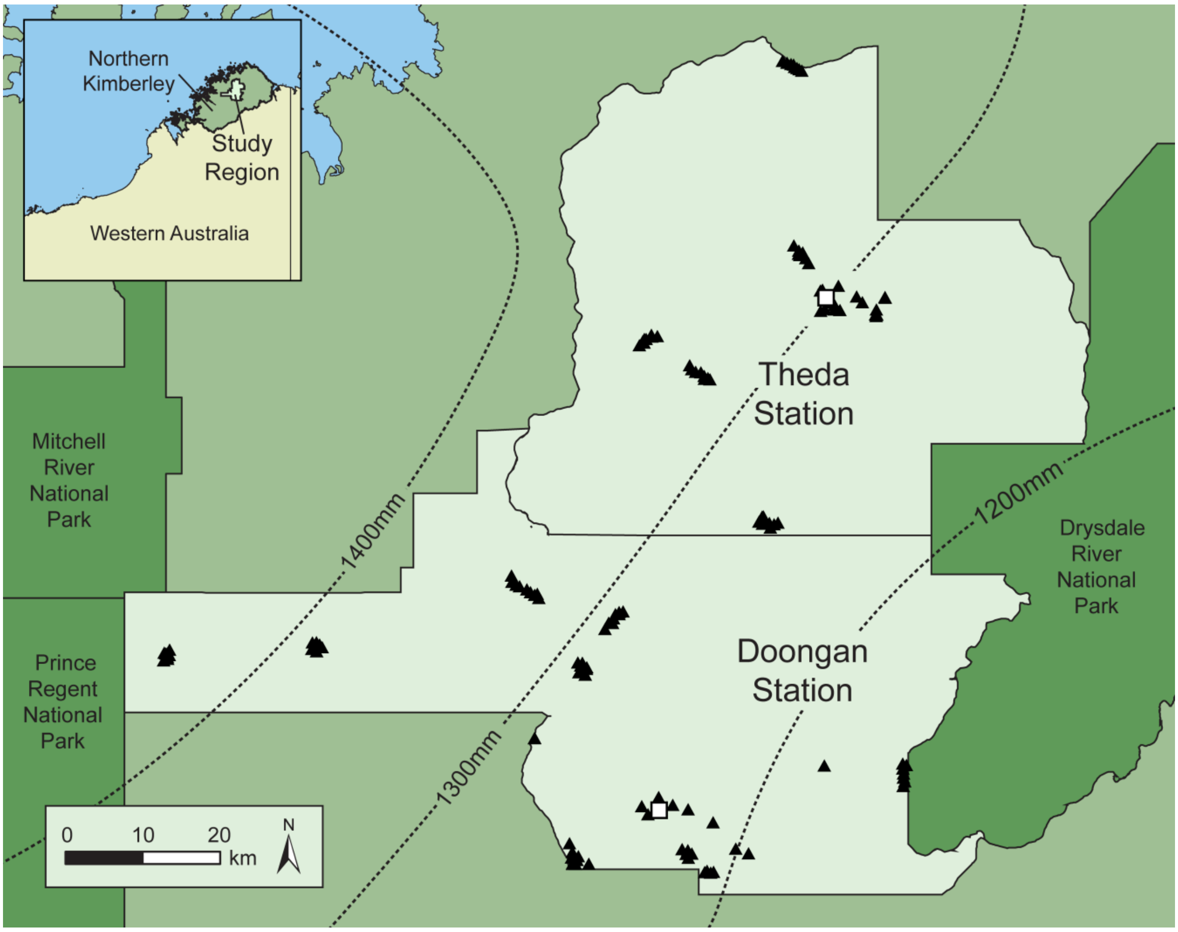

Figure 11. Study region and study sites in the Northern Kimberley, Western Australia.

Triangles represent study sites. Squares represent station homesteads. Dashed lines represent average rainfall isohyets from Bureau of Meteorology (2015a). Inset shows Northern Kimberley and study region in relation to Western Australia.

Table 18. Small mammal species recorded during trapping surveys from 2008 to 2014 inclusive.

Weights after Menkhorst and Knight (2004) and Start *et al.* (2007). * denotes species excluded from models due to low numbers of records.

Species	Body Mass (g)	No. of Records
Leggadina lakedownensis	15-25	18
Pseudomys delicatulus	6-12	72
Pseudomys nanus	25-50	202
Rattus tunneyi	130	441
Zyzomys argurus	35-75	89
Hydromys chrysogaster *	620-1200	5
Planigale maculata *	4-12	8
Pseudantechinus ningbing *	15-33	8
Sminthopsis virginiae	18-75	238
Dasyurus hallucatus	300-1000	13
Isoodon macrourus	500-2000	47
		1120

4.4.4 Environmental data

Spatial analyses were conducted in ArcGIS 10.2 using tools in the Spatial Analyst extension. Land systems describe patterns of topography, vegetation, and soils and their underlying geology (Christian and Stewart 1953). This type of consolidation has been used widely in Australia for mapping resources (CSIRO 2016) and enables recurring patterns in the landscape to be identified (Christian and Stewart 1953; Payne and Schoknecht 2011). Land system was identified on-ground and spatially cross-referenced according to the land system classifications of the Kimberley region (Payne and Schoknecht 2011). The type of rock was also identified on-ground and was spatially cross-referenced according to the surface geology of Australia (Raymond *et al.* 2012). The trapping effort undertaken across the land system and rock type classifications is summarised in Table 19.

Table 19. Number of trap nights for Elliott, cage and pitfall traps, undertaken in the different land systems and rock types.

Definitions after Speck *et al.* (1960), Tille (2006) and Payne and Schoknecht (2011)

	Elliott	Cage	Pitfall	Description of land system / rock type
Land system				
Barton	3328	896	350	Gently undulating volcanic country with grassy woodland vegetation and shallow or leached soils.
Buldiva	8151	1900	972	Rugged sandstone country with open forest vegetation on sandy soils with rock outcrops.
Foster	6332	1684	952	Laterite capped volcanic mesa and plateau country with open forest vegetation and gravelly soils.
Napier	3280	848	452	Hilly volcanic country.
Pago	10448	2196	1664	Gently undulating sandstone country with open forest vegetation and deep sandy soils.
Rock type				
Basalt	3808	992	452	Carson Volcanic predominantly amygdaloidal basalt, interbedded feldspathic quartz sandstone, minor micaceous siltstone and basalt agglomerate.
Laterite	5412	1432	964	Lateritic duricrust that overlays basalt or undulating shale-sandstone country.
None	8912	2104	1344	Mixed deep soils with no protruding rock.
Sandstone	13407	2996	1630	King Leopold Sandstones of medium- to coarse-grained quartzite of outcrops and scarps, with skeletal soils.

Seasonal rainfall was derived from monthly rainfall records interpolated at a 5 km resolution (Jones *et al.* 2009; Bureau of Meteorology 2014) with the values calculated by summing the monthly grids.

Fire data were obtained from the North Australian Fire Information (NAFI) website (http://firenorth.org.au). Yearly fire scar polygons denote the month in which the scar was detected and are derived from 250m resolution Moderate Resolution Imaging Spectroradiometer (MODIS) imagery. Time since fire was calculated as the number of months since a fire scar was recorded prior to site surveys being undertaken, whilst fire frequency was calculated as the number of times the site burnt in the three years prior.

4.4.5 Data analyses

All analyses were conducted in the statistical computing language R version 3.1.2 (R Core Team 2014). We used multivariate generalized linear models (GLM) (function *manyglm* in the *mvabund* package) (Wang *et al.* 2012) to model variance in community composition among sites as a function of land system, rock type, fire history and rainfall (Table 20). Preliminary examination of the data suggested that some explanatory variables had unimodal relationships with the response variable. Consequently, where appropriate, we included quadratic terms to model the non-linear component of the relationships. Negative binomial regression structure was specified in our models to correct for overdispersion. The Wald test was applied to the output from the resampling procedure (5000 permutations). The Wald test statistic estimates the covariance matrix of parameter estimates using a generalised estimating equation approach, with a sandwich-type estimator (Warton 2011), to account for correlation between the environmental variables (Wang *et al.* 2012; Wang *et al.* 2015).

Table 20. Environmental variables included in the *mvabund* modelling of the small mammal community.

* Unburnt sites were scored as 130 months; data available from 2000 onwards.

Variable	Data Source and Notes	Value Range
Number of traps	Number of traps set at the site.	1-25
Type of trap	Type of trap set at the site.	Elliott, cage, pitfall
Number of nights	Number of consecutive nights traps were open.	3 - 4
Land system	Land system classification from Payne and Schoknecht (2011) .	Barton, Buldiva, Foster, Napier, Pago
Rock type	Type of surface rock present at the site at the time of trapping.	Basalt, Laterite, Sandstone, None
Time since fire	Number of months prior to trapping that the site was last burnt.	0-118*
Fire frequency	Number of times that the site burnt in the three years prior to trapping.	0-4
Rainfall of wet season immediately prior	Total rainfall in the wet season (October to April) prior to trapping.	937-2653 mm
Rainfall during two wet seasons prior	Total rainfall in the wet season (October to April) two wet seasons prior to trapping.	929-2549 mm
Rainfall during three wet seasons prior	Total rainfall in the wet season (October to April) three wet seasons prior to trapping.	937-2653 mm
Rainfall during four wet seasons prior	Total rainfall in the wet season (October to April) four wet seasons prior to trapping.	785-2472 mm
Rainfall of dry season immediately prior	Total rainfall in the dry season (October to April) prior to trapping.	0-268 mm
Rainfall during two dry seasons prior	Total rainfall in the dry season (October to April) two dry seasons prior to trapping.	0-219 mm
Rainfall during three dry seasons prior	Total rainfall in the dry season (October to April) three dry seasons prior to trapping.	0-246 mm
Rainfall during four dry seasons prior	Total rainfall in the dry season (October to April) four dry seasons prior to trapping.	0-216 mm
Rainfall gradient	Annual average rainfall extracted from ASCII grid.	976-1220

4.5 Results

4.5.1 Land system

Variation in community composition was associated with land system (P<0.0001; Table 21). The Barton and Napier land systems generally supported *P. nanus*, *R. tunneyi* and *S. virginiae*, with *I. macrourus* occasionally being present (Table 22). Similarly, the Pago land system was predominantly associated with *P. nanus*, *R. tunneyi* and *S. virginiae*, but instead with *P. delicatulus* present, whilst the Foster land system additionally supported *L. lakedownensis*. The greatest difference was observed with the Buldiva land system, which was associated with *Z. argurus* and *R. tunneyi*, with *P. nanus, I. macrourus* and *D. hallucatus* occasionally being present.

4.5.2 Rock type

The composition of the small mammal community differed with rock type (P=0.004; Table 21). Four species (*P. delicatulus*, *P. nanus*, *R. tunneyi* and *S. virginiae*) were frequently found in all rock types (Table 22). Laterite supported the lowest species richness, with three species being undetected in this rock type (*Z. argurus*, *D. hallucatus*, and *I. macrourus*). Laterite was, however, associated with *L. lakedownensis* presence. The presence of *Z. argurus* and *D. hallucatus* in the small mammal community was associated with sandstone.

4.5.3 Time since fire and fire frequency

Time since fire was strongly correlated (P<0.0001) with both the abundance and the composition of species within the small mammal community (Table 21). The abundance of most species was highest between 12 to 24 months since fire. *Pseudomys nanus* was positively associated with 0 – 24 months since fire, whilst *L. lakedownensis* was positively associated with 6-24 months (Figure 12), and *P. delicatulus* was positively associated with 6-30 months since fire (Figure 12). Conversely, abundance of both *R. tunneyi* and *S. virginiae* was negatively associated with time since fire and decreased in relative abundance between 0 to 48 months after fire. *Isoodon macrourus* abundance also decreased with time since fire, but then increased in long unburnt sites (>120 months;

Figure 12) and was the only species to be positively associated with no fire occurring for more than 10 years. The abundance of all of the other species decreased after 48 months since fire, with *Z. argurus* and *D. hallucatus* showing no association other than this. The frequency of burning in the three years prior to trapping was not associated with small mammal community composition or abundance.

Table 21. Effects of land system, rock type, fire and rainfall on the small mammal community using multivariate generalised linear models (GLM) .

The residual degrees of freedom (Res. df) are for linear and quadratic components in the significance test (Wald, P). Superscript indicates quadratic term used in models.

	Df.	Res.df	Wald	P
(Intercept)		1109		
Number of traps	1	1108	20.518	<0.0001
Type of trap	2	1106	6.48	0.001
Number of nights	1	1105	1.692	0.511
Land system	4	1101	17.572	<0.0001
Rock type	3	1095	6.477	0.004
Time since fire	1	1100	6.766	<0.0001
Time since fire^2	1	1099	6.871	<0.0001
Fire frequency	1	1098	3.405	0.21
Rainfall of wet season immediately prior	1	1094	6.356	<0.0001
Rainfall during two wet seasons prior	1	1093	3.725	0.109
Rainfall during two wet seasons prior ^{2}	1	1092	4.44	0.012
Rainfall during three wet seasons prior	1	1091	10.469	<0.0001
Rainfall during three wet seasons prior^2	1	1090	4.701	0.005
Rainfall during four wet seasons prior	1	1089	6.729	<0.0001
Rainfall during four wet seasons prior^2	1	1088	4.934	0.002
Rainfall of dry season immediately prior	1	1087	4.2	0.02
Rainfall during two dry seasons prior	1	1086	4.544	0.002
Rainfall during two dry seasons prior^2	1	1085	5.135	<0.0001
Rainfall during three dry seasons prior	1	1084	3.04	0.278
Rainfall during three dry seasons prior^2	1	1083	3.498	0.091
Rainfall during four dry seasons prior	1	1082	3.081	0.245
Rainfall during four dry seasons prior^2	1	1081	2.601	0.459
Mean annual rainfall	1	1080	4.439	0.006
Mean annual rainfall^2	1	1079	4.53	0.003

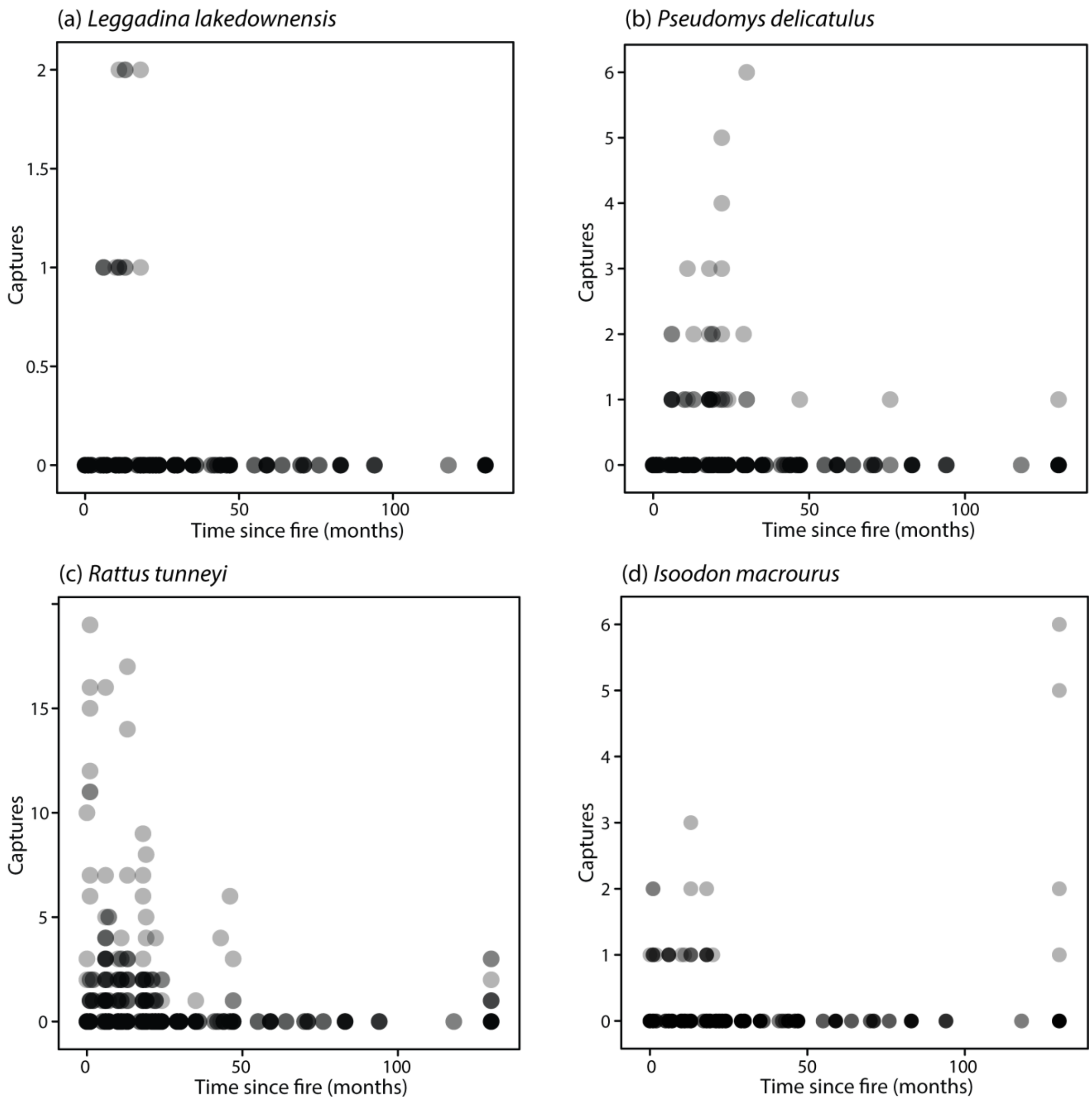

Figure 12. Relative abundance of (a) *Leggadina lakedownensis*, (b) *Pseudomys delicatulus*, (c) *Rattus tunneyi* and (d) *Isoodon macrourus* during site surveys with the time since the last fire (months).

Grey dots represent species' captures per site survey. Darkness of dots represents density of points.

Table 22. Captures per 100 trap nights for each species within the small mammal community for the different land systems and rock types.

E= Elliot trap; C = cage trap and P = pitfall trap.

	L. lakedownensis			*P. delicatulus*			*P. nanus*			*R. tunneyi*			*Z. argurus*			*S. virginiae*			*D. hallucatus*			*I. macrourus*		
	E	C	P	E	C	P	E	C	P	E	C	P	E	C	P	E	C	P	E	C	P	E	C	P
Land system																								
Barton	-	-	0.3	-	-	0.3	1.6	0.3	0.9	1.5	0.6	0.3	0.1	-	-	1.3	-	2.0	-	-	-	0.1	0.8	-
Buldiva	-	-	-	-	-	0.1	0.1	-	0.1	0.4	0.1	0.1	0.7	0.4	0.1	0.1	-	0.3	0.1	0.3	-	-	0.8	-
Foster	0.2	-	0.1	0.1	-	0.2	0.8	0.1	0.5	0.6	0.1	-	-	-	-	0.8	-	0.6	-	-	-	-	-	-
Napier	-	-	-	-	-	-	1.4	0.1	0.2	5.8	1.1	2.9	0.1	-	-	1.8	-	2.4	-	-	-	0.1	2.0	-
Pago	-	-	-	0.4	-	1.1	0.2	-	0.2	0.9	0.2	0.1	0.1	-	-	0.5	0.1	0.2	-	-	-	-	-	-
Rock type																								
Basalt	-	-	0.2	-	-	-	1.2	0.1	0.2	4.3	0.8	2.7	0.1	-	-	1.6	-	2.7	-	-	-	0.1	1.6	-
Laterite	0.2	-	0.1	0.1	-	0.2	0.7	0.1	0.6	0.6	0.1	-	-	-	-	0.7	-	0.3	-	-	-	-	-	-
None	-	-	-	0.2	-	1.0	0.8	0.1	0.4	1.6	0.4	0.1	-	-	-	0.9	0.1	1.0	-	-	-	0.1	1.0	-
Sandstone	-	-	-	0.2	-	0.5	0.2	-	-	0.5	0.1	0.1	0.6	0.3	0.1	0.2	-	0.1	-	0.2	-	-	0.1	-

4.5.4 Rainfall during the wet season

Evidence of a time-lag was found in the effects of rainfall on the small mammal community. The small mammal community was negatively associated (P<0.0001) with the amount of rain in the months prior to trapping, particularly for the abundance of five species (*P. delicatulus*, *P. nanus*, *R. tunneyi*, *S. virginiae* and *Z. argurus*). Conversely, there was a small positive effect of wet season rainfall for *I. macrourus*, whilst there was little effect for *L. lakedownensis*. The amount of rain during two wet seasons prior to trapping showed a variable effect for which the quadratic term demonstrated a significant association (P = 0.012). The relative abundance of *P. delicatulus* appeared to increase, whilst *P. nanus* decreased, with increasing rainfall during two wet seasons prior to trapping. There was little effect on *R. tunneyi*, *S. virginiae* and *I. macrourus*. However, the rainfall three seasons prior to trapping was significant (P<0.0001) and showed a positive effect for *P. delicatulus, P. nanus*, *R. tunneyi*, *S. virginiae* and *Z. argurus*. Similar associations were observed for four wet seasons prior to trapping (P<0.0001), with positive associations for *P. nanus*, *R. tunneyi* and *S. virginiae*.

4.5.5 Rainfall during the dry season

Dry season rainfall immediately prior to trapping significantly affected (P=0.02) the small mammal community. Rain in the two dry seasons (P=0.002) prior to trapping was statistically significant, with the quadratic term also demonstrating a significant association community composition (P < 0.0001). However, neither the dry season rainfall three nor four years prior to the trapping were statistically significant, and no clear positive or negative associations with the small terrestrial mammal community were evident.

4.5.6 Mean annual rainfall

Both linear and quadratic regressions showed mean annual rainfall had a significant effect on small mammal community composition (P = 0.006 and P = 0.003; Table 21). *Rattus tunneyi* and *I. macrourus* were positively associated with higher rainfall. *Pseudomys delicatulus* and *L. lakedownensis* were absent from the community when rainfall exceeded 1150mm. Conversely, *I. macrourus* and *D. hallucatus* were absent from the community when rainfall was below 1100mm. The presence of *Z. argurus* and *S. virginiae* did not appear to be positively or negatively associated with mean annual rainfall.

4.5.7 Trapping method

The type of trap employed showed a significant effect (P=0.001; Table 21) on the small mammal community being detected. All of the species were present in Elliott traps. *D. hallucatus* and *I. macrourus* were not recorded in pitfall traps, whilst *L. lakedownensis* and *P. delicatulus* were not recorded in cage traps.

4.6 Discussion

This study confirms that the small mammal community is influenced by both fire patterns and rainfall variation. Additionally, the composition of the small mammal community also differs both across different land systems and in response to environmental variation. Assumptions about the influence of broad-scale environmental variables on the small mammal community in the NOK have historically been made using knowledge from elsewhere in northern Australia (McKenzie *et al.* 2009; Fitzsimons *et al.* 2010). However, emerging data are improving our understanding of the possible effects of environmental processes in the NOK (Radford *et al.* 2014). The findings in our study strengthen our knowledge of the influence of broad-scale factors on the small mammal community in the NOK, although some findings are not consistent with some of the currently accepted hypotheses.

4.6.1 Trap Success

We included differentiation of the trapping effort and trap types in our model. Recent findings that trapping method in the NOK does not bias the small mammal assemblage being measured, not even for small dasyurids when employing pitfall traps (Radford *et al.* 2014). However, it is generally accepted that species detectability varies with survey technique, and that determining the range of species present in a community requires an array of sampling methods (Garden *et al.* 2007). Our findings indicate that the trap method did influence the community being detected in the current study. Variation in the detectability of species using different trapping methods has shown that diet, body size, trap avoidance and habitat use all contribute to the species' detectability (Laurance 1992; Garden *et al.* 2007). As such, using different types of traps will likely census only a subset of the species within the community of interest. Differences in trap success between Elliott, cage and pitfall traps were also previously documented for the data used in this study (Olds *et al.* 2016b [Chapter 2]), and a bias may have been introduced with fewer pitfall traps being set in rocky sites. Additionally, rocky sites were not evenly distributed between land systems (ie by geology). This potentially creates a bias in the trap records, and our data should be interpreted in the light of this possible confounding effect.

4.6.2 Land system and rock type

Land system appears to correspond with the presence of species within the small mammal community. For instance, the presence of *P. delicatulus* within the community, as opposed to *L. lakedownensis*, was reflected in a shift from the Pago to the Foster land systems. Similarly, the presence of *Z. argurus* and *D. hallucatus* within the community was associated with the Buldiva system. Doongan and Theda Stations are dominated by the Pago and Foster land systems, which likely explains *P. delicatulus* and *L. lakedownensis* being recorded more frequently on these stations (Olds *et al.* 2016b [Chapter 2]; Olds *et al.* 2016b [Chapter 2]) compared to the adjacent Buldiva dominated national parks (Payne and Schoknecht 2011). In fact, records of both *L. lakedownensis* and *P. delicatulus* across the NOK region closely align with the Foster and Pago land systems respectively (DPAW 2015b). The strong associations with land systems suggests that it may be a useful predictor of community composition and a particularly useful consideration when undertaking targeted surveys.

Similar to land system, rock type is a function of the underlying geology. Given the association of land system with the small mammal community, it is within reason that rock type was also strongly associated. Underlying rock provides parent material for soils and undergoes surface processes, such as weathering, that sculpt the landscape (Pepper and Keogh 2014). As such, the type of surface rock also affects communities from a structural and functional perspective. Rocky areas are thought to be key to the persistence of a number of rock-dwelling species in the NOK (Hohnen *et al.* 2015b). The dissected nature, large crevices and complexity of the sandstones and basalts, may offer refuge to some of the small mammal species and afford protection from influences such as fire and cattle (Pepper and Keogh 2014).

4.6.3 Fire

We found small mammal community composition changed between 0 and 48 months since fire, with the greatest species diversity between 6 and 24 months since fire. This finding differs somewhat from findings elsewhere in the NOK. For instance, Radford *et al.* (2015) found no correlation of mammal diversity with diversity of post-fire age classes. Our results indicate that although the communities were of a similar diversity, they are likely to have different compositions. In the Central Kimberley, species richness and abundance was lower in burnt than unburnt patches when compared 5 weeks following an extensive fire, and similar to our findings, both *R. tunneyi* and *P. delicatulus* were present in the small mammal community (Legge *et al.* 2008). The scale at which time since fire is being measured may also be important. Coarser measures (for instance years rather than months) reduce the ability to discern fine-scale differences. The cause of the absence of species in the six months following fire cannot be determined in the present study, but it is likely to be due to a combination of direct mortality and emigration (Radford 2010).

Fire frequency during the three years prior to trapping showed little association with the small mammal community in the current study. It has been historically considered as a key contributor to species declines in northern Australia (Radford 2010). Burning over consecutive years has been shown to create woody thickening in vegetation and to reduce floristic diversity (Bastin *et al.* 2003; Vigilante and Bowman 2004a), and as such, fire frequency might be expected to impact species' ability to recover and/or recolonise. However, we found little association between fire frequency and the small mammal community in the current study. This lack of association has also been shown to be the case in the NOK and the Northern Territory (Lawes *et al.* 2015; Radford *et al.* 2015). The regenerative power of the wet season seems to partially counteract changes created during the dry season. Recently macroinvertebrates in the grass layer have also been found to recover in only one to two wet seasons following fire (Radford and Andersen 2012).

The spatial extent of fires was not considered here, although it may play an important role in determining the post-fire response of the small mammal community (Yates *et al.* 2008; Lawes *et al.* 2015). Whilst prescriptive fires are being ignited early in the dry season, when fuel load is lower and flammability is reduced (Legge *et al.* 2011b), unintentional fires do occur late in the dry season (Vigilante *et al.* 2004). These late season burns tend to be both more extensive and more intense. Extensive fires create large patches of habitat of the same fire-age, increase landscape homogeneity and increase the dispersal distances required for small mammals to reach cover or refuge. Thus, it is logical to conclude that if the ability of the small mammal community to recolonize is hindered (Radford 2010), whether through mortality, dispersal distance or structural changes (Radford *et al.* 2015), the small mammal communities at these sites are likely to be adversely affected, or at least take longer to repopulate areas.

4.6.4 Rainfall

The rainfall during the dry season prior to trapping, as well as two seasons prior to trapping, influenced the composition of the small mammal community. In the short-term, higher rainfall during the dry season may increase soil moisture, and subsequently reduce the severity of the dry conditions and potentially reduce resource pressure (Madsen and Shine 1999), which may have implications for demographic factors such as reproductive output, survival and dispersal (Madsen and Shine 1999). Dry season rainfall has been found to affect the rate of water use during both the dry and the subsequent wet seasons in some of the eucalypts (*Eucalyptus tetrodonta*, *E. miniata*, *E. terminalis* and *E. latifolia*) in northern Australia (Eamus *et al.* 2000). It is possible that the dry season rainfall has broader implications for other plant species, which in turn, influences small mammals that feed on and shelter in vegetation.

The small mammal community was also influenced by the antecedent wet season rainfall. Recently, a positive association has been found between the wet season rainfall prior to trapping, but only with the combined trap success of small mammals >150g, and only in non-rocky savanna (Radford *et al.* 2014), while small mammals <150g and those in rocky-savanna showed no association. In contrast, our data show every wet season up to four years prior to trapping as influencing the small mammal community. Indeed, the smaller species (<150g; *P. delicatulus*, *P. nanus*, *R. tunneyi* and *S. virginiae*) were strongly influenced by the rainfall in the three and four wet seasons prior, an observation which has not been previously reported for the NOK. Our findings suggest there may be delayed changes in small mammal abundance as a result of rainfall variation and there may be a cumulative effect of high rainfall seasons. In arid systems, increases in the densities of rodents in relation to changes in primary productivity (rainfall driven) are similarly delayed (Letnic *et al.* 2005). The amount of rainfall during both the wet and the dry season varies annually in the NOK (Shi *et al.* 2008) with the findings here supporting the notion that the abundance of fauna in northern Australia is being influenced by rainfall (Woinarski *et al.* 2005). Investigation into how rainfall influences changes in on-ground habitat would provide insight into the possible causal factors or at least further elucidate the relationships.

The rainfall gradient of approximately 250 mm across Doongan and Theda Stations was sufficient to influence the small mammal community. In northern Australia, higher rainfall areas tend to support both a higher abundance and a greater diversity of fauna (Radford *et al.* 2014; Turpin 2015). The higher rainfall areas in the NOK also tend to be more rugged and physically complex. The absence of *I. macrourus* and *D. hallucatus* from the community below 1100 mm follows current distribution assumptions for these two species, although isolated *D. hallucatus* populations are known to occur in lower rainfall such as at Mornington Station (Woinarski *et al.* 2014). The current distributions of a number of NOK species are largely or totally confined to the high-rainfall coastal part of the bioregion (Woinarski *et al.* 2014). Whilst both *D. hallucatus* and *I. macrourus* have suffered declines across northern Australia, probably due to changed fire and grazing regimes (Woinarski *et al.* 2014), it is also possible that the lower rainfall areas are inherently less productive and that this could account for these species' absence from those areas.

4.6.5 Landscape productivity and other factors

Our study indicates that productivity in the NOK influences the small mammal community through a composite of mechanisms. The combination of rainfall, fire, edaphic factors and topography, contributes to the productivity of the landscape (Craig 1997). In the NOK, the concentration of rain during the protracted wet season, in conjunction with the contrasting dry season, has contributed to the physiography of the region (Pepper and Keogh 2014). It is largely responsible for the active erosion on the areas of high relief, as well as strong leaching of permeable soils (Speck *et al.* 1960).

Higher rainfall areas tend to be more productive (Devi Kanniah *et al.* 2010; Kanniah *et al.* 2011), and as mentioned previously, there is a rainfall gradient towards the northwest coast (Bureau of Meteorology 2015a). More elevated landscapes generally have greater run-off, and consequently tend be less productive (Hodgkinson and Freudenberger 1997). The land systems describe different environmental conditions, including lithography, surface properties and vegetation, which differ in their soil fertility, proneness to leaching, flooding and erosion (Christian and Stewart 1953). As such, the land systems are likely to differ in their responses to rainfall and fire, and as a result, in their productivity. For instance, volcanic soils, such as those derived from basalt, tend to be more fertile and extensive and may support more productive systems than sandstone derived soils, where soils are generally shallow with bedrock outcrops (Craig 1997; Wende 1997). Olds *et al.* (2016a [Chapter 3]) reported increases in relative abundance, particularly for *R. tunneyi* and *I. macrourus*, to be greatest in basaltic habitats. Conversely, little influence of rainfall was found for *Z. argurus*, whose presence in the community was associated with the Buldiva land system. The Buldiva land system has angular drainage and does not flood during the wet season (Payne and Schoknecht 2011). Thus, it would be less prone to rainfall driven fluctuations in productivity and correspondingly, rainfall has less influence on the community (ie *Z. argurus* and *D. hallucatus*) inhabiting these areas of higher-relief.

Bottom-up controls appear to drive the natural fluctuations in the small mammal community in the current study. However, resources do not appear to be limiting in the NOK savanna (Radford 2010). The effect of resource limitation may be less influential here than in temperate and desert systems due to the monsoonal rainfall that occurs in northern Australia (Devi Kanniah *et al.* 2010). Some invertebrates (Andersen and MÜller 2000; Radford and Andersen 2012) and in the current study, small mammals, appear to recover following fire after two or three wet seasons. Bottom-up pressures may be exerted in the short-term, perhaps immediately following a fire or during exceptionally dry seasons. The influence of top-down pressures, such as predators, were not measured in the current study and hence their interactions and influence on the small mammal community cannot be determined here. However, this additional complexity likely affects small mammals across the landscape, and has been linked to changes following burning (Dickman 1996a; Letnic *et al.* 2005; McGregor *et al.* 2014). The reduction in plant cover by fires increases small mammal susceptibility to predation, and both feral cats (*Felis catus*) and dingos (*Canis lupis dingo*) have been found to exploit this (McGregor *et al.* 2014; Leahy *et al.* 2015). Similar effects may also be created by the presence of cattle

(McGregor *et al.* 2014), and although not quantified here, cattle were present on both Doongan and Theda Stations.

4.6.6 Conclusion

The effects of broad-scale environmental variables appear to be synergistic, with variations in landscape productivity influencing community composition. Land systems may describe the likelihood of species being present within the community, whilst environmental variables such as fire and rainfall, influence species' ability to persist or change in relative abundance. However, the relationship of the small mammal community with environmental conditions is complex, particularly in monsoonal tropical savanna, which is a highly dynamic environment. This study improves our understanding of the relative importance of broad-scale environmental factors on the small terrestrial mammal community in the NOK.

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Chapter 5
General discussion

Red-cheeked Dunnart
Sminthopsis virginiae

5.1 Doongan and Theda Stations

This study describes the small terrestrial mammal fauna (non-volant, <2kg) on two previously unsurveyed pastoral stations, Doongan and Theda Stations, in the Northern Kimberley bioregion (NOK). These stations comprise a large area of approximately 6, 650 km^2 of the NOK (84, 200 km^2) and, together, form a corridor between the three major national parks in the region. The small mammal fauna on these stations has not previously been surveyed. As such, the records obtained in this investigation are novel and fill a major gap in knowledge of the distribution and relative abundance of the small mammal species in the NOK region.

Given that the NOK is widely regarded as pristine and as having a relatively high abundance of many northern Australian species, a diversity of species, in abundance, was likely to occur on Doongan and Theda Stations. However, in the current study and contrary to this hypothesis, a low trapping success of small mammals was found. Whilst this is an important finding for the NOK, it also limited the usability of the data, particularly for individual species (see below in Study Limitations).

Nevertheless, twelve small mammal species were found to occur on both stations. These include six species of rodents, three species of dasyurid, along with *I. macrourus*, *P. dahli* and *P. breviceps* (see Table 15). In addition to these, *P. ningbing* was found on Theda but not on Doongan Station. Conversely, *M. burtoni* was the only species not detected on Theda Station that was found on Doongan Station (Table 15). Detailed comparison of the habitats in which species were detected are described in Olds *et al.* (2016b [Chapter 2]) and Olds *et al.* in review ([Chapter 3]). Since the findings for both species presence and trends in abundance were similar for the two stations, the data were pooled for detailed analyses in Olds *et al.* (in prep [Chapter 4]). Justification of the presence and relative abundance, or conversely absence, of each of the species known to occur in the NOK is discussed below (see Small mammals of the Northern Kimberley, page 119).

Temporal changes in trap success were observed across the study. In Olds *et al.* (2016b [Chapter 2]) it was suggested that this may have been due to exceptional sites being surveyed during 2013, however, similar observations described in Olds *et al.* (2016a [Chapter 3]) indicated this was highly unlikely to be the case. Thus, the temporal changes in trapping success of small mammals appear to be changes in the species' abundance and not an artefact of our trapping methods or selection of sites. This was also supported by the detection of small mammals during spotlighting surveys being rare prior to 2013. Increased encounters during spotlighting efforts at this time corresponded to a greater trap success rate, and therefore small mammal abundance.

Changes in the composition of the small mammal community were associated with broad-scale factors, as described in Olds *et al.* (in prep [Chapter 4]). These likely explain the variation observed across the survey efforts reported in Olds *et al.* (2016b [Chapter 2]) and Olds *et al.* (2016a [Chapter 3]), although the presence and relative abundance of a number of species could not be included in the investigation due to too few records rendering them unsuitable for the modelling methods. Fire and rainfall were both found to be important drivers of changes in the small mammal community structure.

5.2 Study limitations

5.2.1 Lack of historical records

Most of the information on the small mammal fauna in the NOK comes from surveys undertaken by The Department of Fisheries and Wildlife in Western Australia in the late 1970's and early 1980's. Surveys were conducted of Prince Regent National Park (PRNP (Miles and Burbidge 1975)), Drysdale River National Park (DRNP (Kabay and Burbidge 1975)), and on the islands of the North-west Kimberley (Burbidge and McKenzie 1978). The Western Australian Museum also conducted a survey of Mitchell River National Park (MRNP) and the Admiralty Gulf in 1976 (Kitchener *et al.* 1981). Few studies have since been undertaken in the NOK. The most recent accounts of mammals in the NOK revisit some of the previously surveyed sites (Start *et al.* 2007; Corey *et al.* 2013), along with records from hiking expeditions (Turpin 2015). Beyond these, other studies include a wide-scale survey of the Kimberley rainforest patches (Friend *et al.* 1991), surveying NOK islands (Gibson and McKenzie 2012), and burning patterns and vegetation responses (Fisher *et al.* 2003; Vigilante *et al.* 2004; Vigilante and Bowman 2004a; Vigilante and Bowman 2004b; Mucina and Daniel 2013). Information is surprisingly sparse for a region that is highly valued for its biological assets (Masini *et al.* 2009).

The mammal fauna of Doongan and Theda Stations has not previously been sampled. This lack of historical records meant there was no reference framework to assess the occurrence, abundance and patterns of small mammal species found in this study. This impeded the ability to benchmark the species' detection given that changes in occurrence and changes in abundance cannot be effectively measured without a robust baseline (Franklin 1989).

Historical data is needed to provide context when establishing the status of species, particularly when determining whether any deleterious changes have occurred. For instance, species' declines observed in Kakadu National Park (Northern Territory), were described as 'critical' as a result of trap success being <2%, given it had historically been recorded at around <10% in 1996 (Woinarski *et al*. 2010). The mean trap success recorded on both Doongan and Theda Stations was < 2% (Table 6 and Table 13) for four of seven years between 2008 and 2014, using comparable trapping methods to those used by Woinarski *et al.* (2010). However, the lack of historical information for the two stations meant a similar comparison to that of Kakadu was not feasible in the current study. Thus, the conservation significance of the low trap success on Doongan and Theda Stations could not be determined. As such, gaining insight into anthropogenic impacts, changes in habitat, and the efficacy and/or impact of changes in land management activities cannot currently be ascertained on a temporal scale beyond the timeframe of the current study. An examination of subfossil records from Doongan and Theda Stations, such as was undertaken in the southwest Kimberley (Start *et al.* 2012b), may reveal the extent and timeframe of possible local extinctions.

The earlier studies of the fauna in the NOK national parks predominantly consisted of the formation of inventories without the apparent inclusion of in-depth analyses. Thus, the comparison of Doongan Station in relation to the NOK national parks is limited to qualitative analyses in this study, as discussed in Olds *et al.* (2016b [Chapter 2]). Comparison of the stations with historical records from the national parks was hindered by insufficient information. For instance, the earlier surveys of PRNP (Miles and Burbidge 1975) and DRNP (McKenzie *et al.* 1975b) provide landscape descriptions of the habitats surrounding the campsites where the observers were based, but the location of traps within those habitats is not detailed. In PRNP, the various species of small mammal that were collected as specimens were tabulated against the habitat in which they were trapped, but beyond this, no further habitat descriptions or analyses are evident (McKenzie *et al.* 1975a). This lack of published detail precludes a comparison of Doongan and Theda Stations with findings from these locations. Start *et al.* (2007) also identified this as a hindrance to extrapolations from their study when they revisited the national park sites, and these authors suggested that sampling efforts were not always accurately recorded in the previous surveys, and furthermore, they suggested that there had previously been some inappropriate pooling of data.

The comparison of Theda Station with Doongan Station in Olds *et al.* (2016a [Chapter 3]) is the first major study to compare the status of small mammal fauna across private leases in the NOK. Although these stations are currently under the same tenure, and subsequently current land management practices, the vast size of the stations and the potential for future change warranted these being considered as separate entities. The findings on Doongan Station at least provided a comparable baseline to interpret the findings on Theda Station, in the absence of historical data. The annual changes described in Olds *et al.* (2016b [Chapter 2]) and Olds *et al.* (2016a [Chapter 3]) underscore the need for collecting and assessing long-term data, generating what should become important historical information in the NOK, both for monitoring species' status and for further insight into drivers of change.

5.2.2 Accessibility

The NOK is one of the most remote and inaccessible regions in Australia. Two main roads service the NOK: the Gibb River Road lies on the southern border of the NOK, traversing east to west, and is joined at a T-junction by the Kalumburu Road, which runs north to south and passes through both Doongan and Theda Stations. These 'main' roads are usually impassable during the monsoon season. Furthermore, since the roads are unsealed, the region is generally only accessible by four-wheel drive, or suitably equipped, vehicles. All other roads, or tracks, are generally maintained by the land holders and are not publicly accessible. As such, vast areas of the region are not reachable by road or track. This inaccessibility of the NOK has been of conservation benefit (McKenzie *et al.* 2009), and is likely to have supported the persistence of the small mammal species. Transportation infrastructure is known to impact both the local and broad-scale environment (van der Ree *et al.* 2011). Increased accessibility brings increased visitation, and a suite of both direct and indirect impacts ranging from pollution, direct mortality of animals, weed dispersal and habitat fragmentation, to the increased occurrence of escaped fire (Jackson 2000; Coffin 2007).

This inaccessibility of the NOK region also means that a significant investment is required in both time and resources to undertake surveys, particularly in travelling to sites. It was often most practical to camp close to the sites during trapping sessions. In doing so, access to potable water was required as it was not feasible to transport sufficient water, along with equipment (both trapping and camping), across the long distances and rough terrain. This placed some limitations on the locality of survey efforts. Furthermore, access to particularly remote areas, such as Woongaroodoo Gorge on Doongan Station, and Mongonai Creek on Theda Station, required helicopter transportation. Undertaking surveys in this manner is often cost prohibitive but logistically the only way to access distant sites. This limited accessibility means that there are still extensive unexplored areas on the two stations and some species, that have thus far been undetected on the stations, may nevertheless be present.

5.2.3 Trapping methodology

Comparison of the findings on Doongan and Theda Stations was limited to qualitative comparison with other studies in the NOK due to incomparable survey methods and paucity in the national park literature. The surveys of the national parks in the 1970's and 1980's were primarily inventorial and did not provide accurate details of trapping effort. Additionally, the methods employed in the early surveys variably included large breakback, small breakback, Victor Rat, small Elliott, large Elliott, Sherman and cage traps, using 'universal bait' (peanut butter, bacon, raisins and oats). As such, the variety of traps and methods employed in the surveys of the parks were notably different from those employed in the current study. Furthermore, the capture method is not described for the animals obtained and for the most part, is limited to 'trapped' (as distinct from 'shot' for example). More recent surveys from 2003-2004 and 2010 – 2012, are more specific in their methods, however their surveys were limited to only a few sites within each nature reserve (Start *et al.* 2007; Radford 2012). Accordingly, the ability to benchmark species' abundance between Doongan and Theda Stations and the NOK national parks is limited. Start *et al.* (2007) have previously recognised this caveat when revisiting the historically surveyed national park sites.

The methodology used in the current study was not without imperfections either. The trapping method employed during 2006 and 2007 inconsistently utilised transects. These were employed in an exploratory method as both Doongan and Theda Stations had not previously been surveyed. Across these two years, there was also variance in both the number of traps deployed and the number of nights that traps were opened, and subsequently the number of trap nights employed during survey sessions. This meant that the data recorded during these two years were not comparable with those from 2008 onwards, and subsequently these data had to be excluded from the modelling presented in

Olds *et al.* (in prep [Chapter 4]). Nevertheless, important information on species presence was recorded in 2006 and 2007. For instance, *M. burtoni* was recorded on Doongan Station in Olds *et al.* (2016b [Chapter 2]), but has not been detected on either Station subsequently. Thus, the species listed in Olds *et al.* (2016b [Chapter 2]) and Olds *et al.* (2016a [Chapter 3]) form an important record for the NOK.

The successful detection of various small mammal species depends upon the survey technique being utilized, and exploratory sampling to determine the range of species present requires an array of sampling methods (Garden *et al.* 2007). This was demonstrated by the variability in capture rates for species using the different types of traps described in Olds *et al.* (2016b [Chapter 2]) and Olds *et al.* (2016a [Chapter 3]), as well as the significance of both the type of trap and the number of traps in the community modelling in Olds *et al.* (in prep [Chapter 4]). The historical surveys of the national parks employed a variety of traps but these were limited to two trigger mechanisms: treadle-style traps and lethal spring traps. Start *et al.* (2007) acknowledge that they did not employ sampling methods effective for detecting small dasyurids and the current study indicates that their lack of detection of two of the small rodent species (*Leggadina lakedownensis* and *Pseudomys delicatulus*) along with *Planigale maculata*, may have been due to the lack of pitfall traps in the previous investigations in the national parks. As such, the disparity in the types of traps employed also limited the ability to compare Doongan and Theda Stations with the national parks.

The type of traps used in the present study was also not optimal for detection of a number of small mammal species on Doongan and Theda Stations. As suggested in Olds *et al.* and Olds *et al.* (2016a [Chapter 3]), the few observations of *H. chrysogaster* were likely to be due to both an inappropriate bait being used and traps being laid on the periphery of the habitat which they tend to utilise. Similarly, the use of terrestrial methods may have contributed to the lack of detection of some semi-arboreal species, including *P. tapoatafa*. However, spotlight surveys should have indicated their presence, as was the case with *P. breviceps*, *P. dahli*, and *W. squamicaudata*, if they had been widely distributed.

Survey methods utilised in future research should be carefully tailored to suit the intention of the survey. For instance, methods should be optimized when targeting specific species, with the full quadrat methodology unlikely to be required. However, maintaining annual surveys using the consistent quadrat methodology, which was used in this study from 2008 onwards, should be carried out for monitoring long-term trends. Furthermore, undertaking repeat surveys at established sites, where possible, would provide the most informative record of change. Lack of long-term data is a hindrance for interpreting ecological studies (Franklin 1989). As shown in Olds *et al.* (2016a [Chapter 3]), the trap success recorded during 2008 was not indicative of 2013, and vice versa. Ad hoc surveys are less reliable in their capacity to indicate change and limit the ability to decipher the causes of change, and consequently to effectively implement management.

5.2.4 Site selection

Site selection can cause significant bias in broad-scale survey efforts, and results need to be considered with respect to the locality of the surveys. Previous studies of the NOK have focused on areas known to support high biodiversity. This is particularly relevant when considering the earlier surveys in MRNP, where for instance, Kitchener *et al.'s* (1981) survey of MRNP in 1976/77 included only approximately 27% of their trap-lines within savanna woodland, whilst other sites were within deciduous vine thicket (22%), riparian (25%), sandstone (17%) and blacksoil/swamp (7%) situations along with one mangrove and one grassland site. Subsequently, the seven sites revisited within MRNP by Start *et al.* (2007) were predominately riparian or sandstone habitats. More recently, the study by Radford (2012) targeted areas in MRNP that were considered to be intact, where rocky shelters and high rainfall have provided protection from fire. This biases the results, which Start *et al.* (2007) duly acknowledge, and indicates that the high abundance recorded by these authors may not be a true representation of the broader condition of the national parks.

Although the earlier surveys of PRNP and DRNP are lacking detailed habitat descriptions of trap locations, the inference of survey bias can be made for PRNP and DRNP sites when they were revisited by Start *et al.* (2007). The four PRNP sites were targeted at riparian and scree sites, whilst the three sites surveyed in DRNP were all riparian sites, two of which comprised mixed woodland with floristically variable sandstone communities and the other a eucalypt woodland. The abundance and richness of the small mammal species observed within these surveys of DRNP and PRNP would have been influenced by their preferential targeting of known biodiversity-rich sites, as is the tendency for many surveys carried out. Such was also the case for Theda Station focusing on sandstone, until the implementation of quadrats enforced sampling of more varied habitats. It is often perceived to be far more interesting to survey such areas, and site choice is biased by anthropogenic preference.

Randomisation of survey sites, including environmental stratification, could help to reduce these biases when designing new surveys or choosing additional sites.

The bias of undertaking surveys within refugia is likely to have influenced the abundance and richness of small mammal species reported within the national parks, and consequently the condition of the NOK was inferred to be pristine. However, the results presented in both Olds *et al.* 2016b [Chapter 2]) and Olds *et al.* (2016a [Chapter 3]) indicate that this is unlikely to be the case, and the broader NOK is not in the 'pristine' condition it is often purported to be.

5.2.5 Ecological modelling

The low trap success described in Olds *et al.* (2016b [Chapter 2]) and Olds *et al.* (2016a [Chapter 3]) posed a major challenge for examining variation in species' presence and abundance. Trapping provides count data, and where few records are obtained, these data become skewed away from a normal distribution. This lack of fit is referred to as being 'zero-inflated' when there is a disproportionately large number of zero observations (Martin *et al.* 2005). Ecological data are often zero inflated, and additionally, are often overdispersed (Martin *et al.* 2005; Warton *et al.* 2016). Such was the case for the data collected on Doongan and Theda Stations, both when considered independently and when pooled (Figure 13).

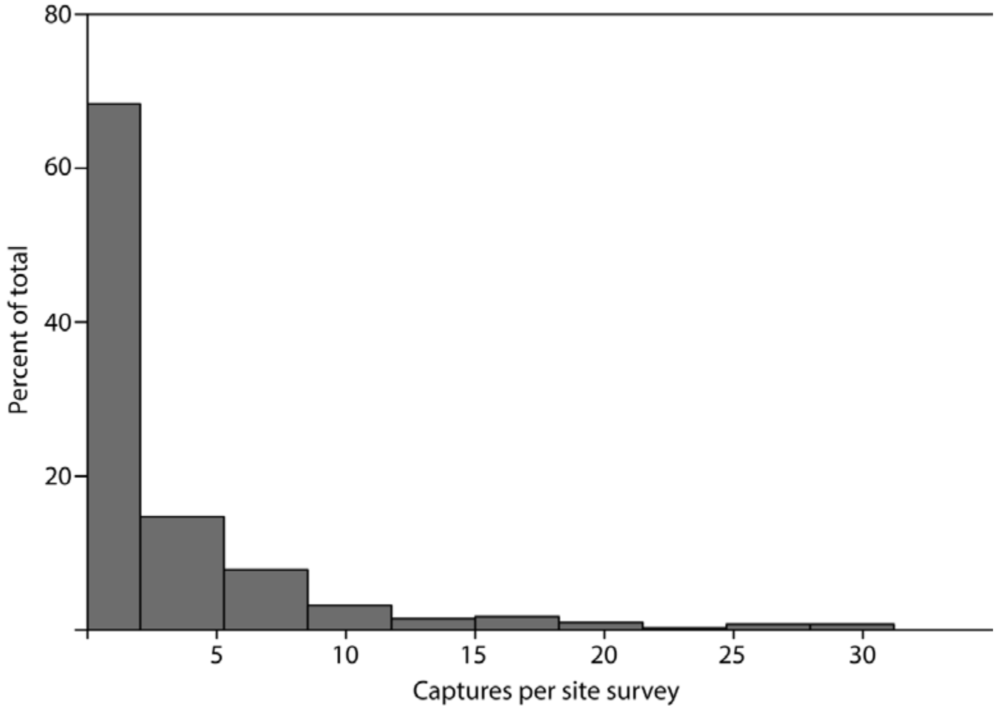

Figure 13. Frequency plot of the pooled small mammal abundance per site survey on Doongan and Theda Stations between 2008 – 2014.

The non-normality of the data presented in Olds *et al.* (2016b [Chapter 2]) and Olds *et al.* (2016a [Chapter 3]) meant the basic requirements for undertaking any parametric analyses were violated and non-parametric methods were employed. In the first instance, Doongan Station could not be statistically compared to other studies in the NOK due to the data originating from markedly different methodology and therefore any formal statistics applied would not be valid (Olds *et al.* 2016b [Chapter 2]). However, comparison of Theda Station to Doongan Station, was possible using non-parametic methods to at least provide some basis for regional comparisons (Olds *et al.* 2016b [Chapter 2]). The data from 2006/2007 was collected using inconsistent methods and so had to be excluded from any statistical testing. Nevertheless, the non-parametric tests applied in Olds *et al.* (2016a [Chapter 3]) were sufficiently informative to identify variations in both the stations' and the species' relative abundances. However, they were limited in their ability to explain why variations in small mammal community composition were observed.

Modelling techniques were used to attempt to explain the community composition (Olds *et al.* in prep [Chapter 4]). Detailed data exploration revealed a number of variables that were originally considered for inclusion in the model construction to be rendered unsuitable. This was primarily due to collinearity and/or abundance of groups with too few records of categorical data, where re-categorisation or pooling would have made the variables uninformative. Failure to explore data prior to analysis is often the first of a set of common statistical errors in ecology (Steel *et al.* 2013) but measures were taken to avoid such in this study.

The aforementioned non-normality of the data meant that classical multivariate techniques (Anderson 2003) were similarly not appropriate for use in Olds *et al.* (in prep [Chapter 4]) of this study. Nevertheless, generalised linear modelling was feasible, but only using the pooled data from 2008 - 2014. Whilst a number of species had to be excluded from the model due to too few records, sufficient records remained to enable models to be constructed.

A ‘model-based approach’ was applied to the small mammal data in this study (Warton *et al.* 2015). This approach allows community ecology to be assessed by explicitly accounting for the uncertainty in the data, whereby the assumptions of the analyses are clearly specified (Warton *et al.* 2015). This was undertaken using a relatively new tool, the *mvabund* package in R. *Mvabund*, which uses hypothesis testing for multivariate data (Wang *et al.* 2012), using a novel set of tools within a generalised linear model (GLM) framework (Warton 2011). The analysis of variance (ANOVA) and model estimations use resampling-based hypothesis testing similar to those used for standard generalised linear modelling techniques. However, inference tools take into account the correlation between species to test community-level hypotheses (Wang *et al.* 2012). This has been used elsewhere for a range of ecological modelling studies (Zhou *et al.* 2013; Moorhouse *et al.* 2014; Decleer *et al.* 2015), but it has not been previously applied to small mammal ecology in northern Australia. The specific modelling results will not be discussed further here, although it should be noted that the modelling was sufficiently robust to be informative of the environmental variables influencing the small mammal community.

5.3 Small mammals of the Northern Kimberley

5.3.1 Muridae (Murinae)

5.3.1.1 Leggadina lakedownensis

Little is known of the ecology of *L. lakedownensis*. In Queensland, this species generally inhabits riparian, water logged or mesic areas, ranging from open grassy woodlands to grasslands on sandy clays, within the tropical high rainfall zone (>600 mm annually) (Cole and Woinarski 2002) (2005). Similarly, in the Northern Territory, *L. lakedownensis* is restricted to grasslands, particularly wet grasslands on clay soils with scattered trees and shrubs (Cole and Woinarski 2002). Contrastingly in the NOK, the presence of *L. lakedownensis* appears to be highly associated with the Foster land system (Olds *et al.* in prep [Chapter 4]). These data also suggested that *L. lakedownensis* was absent from the community when rainfall exceeded 1150mm. It is more likely, however, that this delineation of *L. lakedownensis* presence represented a shift in dominant land systems rather than rainfall gradient.

The Foster land system describes immaturely dissected plateaus with gravelly soils, often with a distinctive understory of *Livistona* spp.. The association of *L. lakedownensis* with lateritic substrates in the NOK has also been found to occur in the Mitchell Plateau area (Bradley *et al.* 1987). As suggested in Olds *et al.* (in prep [Chapter 4]) the lack of detection of *L. lakedownensis* from PRNP community (McKenzie *et al.* 1975a) may be due to the absence of the Foster land system in this park.

Leggadina lakedownensis was not favoured in the community until six months after fire. This may relate to this species' life history. *Leggadina lakedownensis* breeds during the dry season in the Northern Territory, and presumably also in the NOK. Thus, population restoration and dispersal following fire may not be observed until one or two dry seasons have passed (6 – 24 months since fire). Studies of this species on Thevenard Island (Western Australia) have associated abundance with rainfall, particularly after the wet season. However, in the present study, no association was found for *L. lakedownensis* with either wet or dry season rainfall. Greater insight into this species' ecology would be gained from further investigation of the records of *L. lakedownensis* from Doongan and Theda Stations.

5.3.1.2 Pseudomys delicatulus

Pseudomys delicatulus presence in the small mammal community was predominantly associated with the Pago (undulating sandstone country) land system (Olds *et al.* in prep [Chapter 4]). It was recorded on sandstone plains with deep sandy soils, predominantly in woodlands dominated by *E. miniata*, *E. tetrodonta*, *P. pubescens* and occasionally *Grevillea agrifolia* over native grasses, but was also detected on creeklines, sandstone outcrops and a laterite flat (Olds *et al.* 2016b [Chapter 2]; Olds *et al.* 2016b [Chapter 2]).

These findings supports its preference for deep sandy soils, with grassland and open woodland vegetation (Ford 2008), along with alluvial soils in river fringing formations (Kerle and Burgman 1984).

Pseudomys delicatulus breeds in high resource times such as the wet season (although it can be a continuous breeder) (Ford 2008), and may require one or two wet seasons for populations to recover following fire. This also aligns with *P. delicatulus*' presence within the community being associated with a fire frequency of one burn in three years (Olds *et al.* in prep [Chapter 4]). However, results in Olds *et al.* (in prep [Chapter 4]) indicated that *P. delicatulus* was positively associated with 6-30 months since fire. This somewhat contradicts findings for *P. delicatulus* in the Central Kimberley where it was present within 5 weeks following fire (Legge *et al.* 2008).

Recent taxonomic studies of *P. delicatulus* have shown that the western populations are probably a separate species from the Queensland and Northern Territory forms (Breed and Ford 2007). The *P. delicatulus* spermatozoa from Theda Station was found to be variable, but generally pear-shaped (Olds *et al.* 2016b [Chapter 2]). This morphology was most similar to observations in the top end of the Northern Territory and northwest WA (Breed 2000). Comparatively less variability in morphology is shown in spermatozoa from Queensland and Groote Eylandt *P.* delicatulus along with these showing a tendency to have bilaterally flattened heads with the tail attached to the lower concave surface (Breed 2000; Thalli Moya-Smith and Bill Breed unpublished observations). As suggested in These observations suggest that the animals in the western part of the range of *P. delicatulus*, including those obtained in the current study, are a separate species from those occurring in eastern Australia and on Groote Eylandt. The variability of their sperm head and comparatively short sperm tail compared to other *Pseudomys* species (see Breed and Taylor (2000)) indicates that this species has a monogamous breeding system as suggested in Chapter 3 (Calhim *et al.* 2007; van der Horst and Maree 2014; Varea-Sánchez *et al.* 2014). However, further analyses and the inclusion of more samples from across a wider distribution would be beneficial for the resolution of this species' taxonomy.

5.3.1.3 Pseudomys johnsoni

Pseudomys johnsoni was originally described in 1985 from the Murchison Ranges in the Northern Territory (Kitchener 1985). The description of *P. laborifex* came later (Kitchener and Humphreys 1986), and that taxon was subsequently subsumed within *P. johnsoni.*

Its distribution extends from the NOK through sub-tropical Northern Territory into western Queensland (Kerle and Ford 2008).

Pseudomys johnsoni constructs mounds using stones and pebbles and, as such, tends to avoid weathered bedrock, sand and clay substrates (Ford and Johnson 2007). In the Kimberley, it predominantly inhabits open eucalypt woodlands, preferring hummock dominated understoreys. None of the sites on Doongan and Theda Stations were targeted at hummock grasslands on stony hills, such as those described by Ford and Johnson (2007) and Kitchener and Humphreys (1986), and this may explain its lack of detection. The observation of a pebble-mound on Doongan Station (Olds *et al.* 2016b [Chapter 2]) indicates that further searches should be undertaken on the two stations to elucidate the occurrence of *P. johnsoni*. However, general surveys, such as undertaken in the current study, may not be an effective sampling method for this species (Woinarski *et al.* 2014). Searching for its characteristic pebble mounds may be more effective, although the structure of the mounds may not be consistent across its range, thus observations of pebble mounds *per se* should be interpreted with care.

5.3.1.4 Pseudomys nanus

Pseudomys nanus is considered to be a habitat generalist (Robinson and Cooper 2008), a conclusion that is supported by our results. This was the only species found on Doongan and Theda Stations to be detected in all of the 14 broad habitat types surveyed. *Pseudomys nanus* occurs across much of tropical Australia (Figure 6) and has been found in a range of habitats, although tends to prefer dense tussock grasslands and riparian areas (Robinson and Cooper 2008). The least preferred habitat for *P. nanus* appears to be rocky savanna. In the current study, this species was only occasionally present in the Buldiva (rugged sandstone) land system. However, it has been detected in rugged boulder country in both PRNP and MRNP (McKenzie *et al.* 1975a; Kitchener *et al.* 1981) and in the Northern Territory (Price *et al.* 2005).

The ground layer is thought to be important for *P. nanus* (Robinson and Cooper 2008) and the extent of unburnt vegetation was found to be important for *P. nanus* in the NOK (Radford *et al.* 2015). This species has previously shown little association with fire frequency (Radford *et al.* 2015), which the results in this study supports. In the Central Kimberley, *P. nanus* was found to be more common in unburnt than burnt sites immediately following fire (Legge *et al.* 2008). However, our results only partially support this, as it was recorded within the first month following fire. In fact, the presence of *P. nanus* in the small mammal community was associated with the first six months following fire and up to 24 months since fire.

Although *P. nanus* is a relatively common species in northern Australia, little is known about its life history (Robinson and Cooper 2008). It is suspected to be a highly efficient breeder, with three to five young, and a weaning period of only 21 days (Taylor and Horner 1972). As such, it is thought that *P. nanus* is a continuous breeder (Robinson and Cooper 2008). By having reduced parental care and rapid young development, it may be able to recolonise burnt areas quickly (Kerle and Burgman 1984).

5.3.1.5 Conilurus penicillatus

Conilurus penicillatus is restricted to the coastal areas of the NOK and the Northern Territory (Woinarski *et al.* 2014). It has suffered severe decline across its range, including its recent disappearance from Kakadu National Park (Woinarski *et al.* 2014). *Conilurus penicillatus* is known from less than ten localities in the NOK and has always been considered rare in Western Australia (Firth *et al.* 2010; DPAW 2015b), although it was reported as common in the south-west Kimberley at the time of its discovery (Dahl 1897, 1926). It occurs in MRNP and PRNP and has been detected in these national parks in recent years (Start *et al.* 2007; Corey *et al.* 2013).

The Northern Territory/NOK populations are recognised as a separate subspecies from the Tiwi Islands' population (*C. p. penicillatus* and *C. p. melibius* respectively, along with *C. p. randi* in New Guinea), based on morphology (Kemper and Schmitt 1992). This species inhabits open forests with tall eucalypt trees and sparse grass cover. It has been suggested that its persistence in the Tiwi Islands is due to the eucalypt forest on these islands being the tallest in the Northern Territory. Here they also have shown preference for forests distant from wet areas and where fire has been limited, suggesting fire regimes have significantly contributed to its extirpation in other areas. Recent surveys (2011/2012) in the NOK national parks have shown increases in *C. penicillatus* trap success coinciding with improved land management practices, including fire management and cattle culling (Corey *et al.* 2013). As suggested in Olds *et al.* 2016 ([Chapter 2]) and Olds *et al.* (2016a [Chapter 3]), confirmation of the absence of this species from Doongan and Theda Stations would require further survey efforts. These should target tall eucalypt forests that have not been repeatedly burnt, particularly within the last 5 years. Trapping methods should also be considered in targeted efforts, including the placement of traps in trees and the deployment of remote camera traps (Doody *et al.* 2012).

5.3.1.6 Mesembriomys gouldii

The distribution of *Mesembriomys gouldii* has contracted across northern Australia. It is considered to be uncommon in the coastal areas of Cape York Peninsula (Queensland), but is still patchily distributed in the Top End of the Northern Territory (Woinarski *et al.* 2001; Woinarski *et al.* 2010; Ziembicki *et al.* 2013; Woinarski *et al.* 2014). These populations are disjunct with the Northern Territory/NOK, northeast coastal Queensland and Melville Island distributions being recognised as distinct subspecies (*M. g. gouldii, M. g. rattoides* and *M. g. melvillensis* respectively) (Woinarski *et al.* 2014). It has not been recorded in the NOK since the 1980's which has raised concern for its conservation status (Corey *et al.* 2013; Woinarski *et al.* 2014). Whilst tall open eucalypt forests (*E. miniata* and *E. tetrodonta*) were surveyed on Doongan and Theda Stations, these sites did not comprise the midstorey species (such as *Gardenia*, *Terminalia*, *Planchonia*, *Pandanus* species) in the density described as the preferred habitat for *M. gouldii*. Density of these midstorey species, and subsequently *M. gouldii* presence, is often associated with sites protected from fire or perennial soaks and which afford perpetual resources (Friend 1987). Nevertheless, *M. gouldii* has not been recorded in PRNP or DRNP (Start *et al.* 2007), and its lack of recent detection in MRNP (Corey *et al.* 2013) suggests that it is also likely to be absent from Doongan and Theda Stations.

5.3.1.7 Mesembriomys macrurus

Mesembriomys macrurus has recently become extinct in the Northern Territory. This species is now restricted to the NOK region where it is considered to be relatively common in the near-coastal areas (Woinarski *et al.* 2014). The animals have a large home range which reflects this species' high resource needs and, where they still occur, they appear to be sparse because habitat patches can support few individuals (McKenzie and Kerle 2008). Similarly, their current distribution is likely linked to the availability of food resources including fruits, flowers and insects (McKenzie and Kerle 2008), which may be why this species has persisted in the high-rainfall, near-coastal areas but has disappeared from the south-west Kimberley and the Pilbara (Western Australia) (McKenzie 1981; McKenzie and Kerle 2008). Perturbations, particularly those caused by fire, are implicated in their decline although recent declines in the NOK are yet to be evidenced due to lack of data (Woinarski *et al.* 2014). Given that *M. macrurus* has not been recorded in DRNP either (Start *et al.* 2007), it is likely that Doongan and Theda Stations could be within the drier part of the range of this species, and if they occur their density is likely to be low.

5.3.1.8 Melomys burtoni

Melomys burtoni is considered to be widespread in northern Australia (Figure 6) (Woinarski 2000) where it is known to inhabit monsoon rainforests, mangroves and grasslands (Kerle 2008). Within the NOK, it has been found to inhabit deciduous vine thickets and vegetation mosaics (predominantly tidally inundated mangroves) in MRNP (Kemper *et al.* 1987), and river fringing black soil grasslands in PRNP (McKenzie *et al.* 1975a). Recent surveys of these national parks have shown *M. burtoni* still to be relatively common in these areas (Start *et al.* 2007; Corey *et al.* 2013; Radford *et al.* 2015).

On the Tiwi Islands (Northern Territory), this species has been found in highest abundance in coastal and rainforest sites, with fewer detected in eucalypt woodland, and the lowest abundance within eucalypt open forest (Firth *et al.* 2006). Given vegetation density is likely to influence the presence of *M. burtoni*, the rarity of its detection on Doongan Station and lack of detection on Theda Station is likely to be due to the surveyed sites not encompassing its required habitat. Few rainforest patches and vine thickets were surveyed during this study. The rainforest in which the two individuals were detected on Doongan Station was small and isolated (<0.1ha) and this species was not detected in subsequent surveys of the rainforest. This suggests this population has disappeared from this particular rainforest patch across the period of this study. This site should be monitored in the future for the presence of *M. burtoni*. Other rainforest patches should also be surveyed to establish its occurrence and *M. burtoni* presence could be an indicator of past habitat connectivity. Historical land management practices (i.e. presence of cattle and occurrence of fire) may have impacted the more open savanna habitat between suitable patches and subsequently reduced the connectivity between rainforest patches.

Morphological variation in *M. burtoni* has been observed within the NOK and across its range. The need for taxonomic revision has been suggested (Kemper *et al.* 1987; Woinarski 2000) with the current species likely to be separated into multiple subspecies (Woinarski *et al.* 2014). The habitat preferences and occurrence of *M. burtoni* in the NOK should be reviewed following any taxonomic revision.

5.3.1.9 Rattus tunneyi

This study supports *R. tunneyi* being a habitat generalist (Aplin *et al.* 2008) as it was both the most widely distributed and the most frequently recorded rodent on both Doongan and Theda Stations. Monsoon forest was the only broad habitat in which it was not observed (Olds *et al.* 2016b [Chapter 2]). Despite being generally common, declines have been observed in Kakadu National Park (Northern Territory), although, the cause of their decline is yet to be deciphered (Woinarski *et al.* 2010). Further investigation of the data presented in the study may help to elucidate the relationship of *R. tunneyi* with fine-scale habitat conditions, particularly as responses to broad-scale environmental variables were observed (Olds *et al.* in prep [Chapter 4]).

Relatively high capture rates for *R. tunneyi* were obtained on basalt-derived soils, which, as suggested in Olds *et al.* (in prep [Chapter 4]), tend to be more fertile and support more productive systems than sandstone-derived soils. Although *R. tunneyi* showed a marked increase in trap success rates on both stations over the study period, it appeared to be more abundant on Theda Station. On this latter station, a greater trapping effort was undertaken in volcanic habitat and it is possible that the higher productivity of these systems influences the availability of resources, and hence resulted in the greater abundance of *R. tunneyi*. *Rattus tunneyi* is thought to increase in abundance after significant rainfall especially in 'good' seasons (Aplin *et al.* 2008) which this study also supports. The influence of this rainfall may be magnified in productive volcanic sites, and species such as *R. tunneyi* may therefore go through more pronounced local population expansion in these richer habitats following major rainfall events; a suggestion that needs further investigation.

Rattus tunneyi has shown contradictory responses to fire. In the central Kimberley, it was absent from the community immediately following burning (Legge *et al.* 2008). However, in this study its presence and relative abundance was favoured (Olds *et al.* in prep [Chapter 4]). In the Northern Territory, its abundance was found to be favoured with frequent burns (Woinarski *et al.* 2004b; Price *et al.* 2005), however, its presence in the community on Doongan and Theda Stations did not appear to be associated with burning frequency. It is possible that *R. tunneyi* takes advantage of the fresh growth immediately following fire. Its persistence immediately following fire may also be related to its burrowing behaviour (Aplin *et al.* 2008), as it may be able to escape direct mortality during low intensity fires. It may be that the fire observed in the Central Kimberley was too intense for *R. tunneyi* to have survived the burn. It appears that *R. tunneyi* is sensitive to changes in the environment. Given it is a relatively common species in the NOK, and readily trapped, it may serve as a useful indicator species for changing environmental conditions.

5.3.1.10 Zyzomys argurus

The results from both Doongan and Theda Station (Olds *et al.* 2016b [Chapter 2]; Olds *et al.* 2016b [Chapter 2]) support the known habitat associations of *Zyzomys argurus* with rocky boulder country (Fleming 2008). *Zyzomys argurus* was predominantly detected on rugged sandstone and outcrops (Table 7 and Table 14), with shallow sandy soils and vegetation communities variably including *E. miniata*, *E. tetrodonta*, *Owenia vernicosa*, *Xanthostemon sp*, *Gardenia megasperma*, *Terminalia sp.* and *Calytrix sp.* over hummock and annual sorghum grasses. The only *Z. argurus* individuals not recorded on sandstone on Doongan and Theda Stations were captured on Carson volcanics. It has previously been observed on volcanics in the MRNP, although it was found to prefer sandstone to volcanic substrates (Kitchener *et al.* 1981) and, despite extensive trapping in PRNP, it was not observed on volcanics in that area (McKenzie *et al.* (1975a).

The association of *Z. argurus* presence with the Buldiva land system (Olds *et al.* in prep [Chapter 4]) is supported by the findings presented in Olds *et al.* 2016b [Chapter 2]) and (Olds *et al.* 2016b [Chapter 2]). The Buldiva land system describes rugged sandstone county, with rocky pavements and dissected plateaux, and open woodland vegetation with pockets of grasses. Kitchener and Keller *et al.* (1981) found *Z. argurus* to have a positive association with the presence of hummock grasses (when compared to the absence of hummock grasses). Similarly in the Northern Territory, *Z. argurus* has been negatively associated with tree species richness (Trainor *et al.* 2000), suggesting a preference for sparser woodlands with hummock understoreys.

Little association was found for the presence of *Z. argurus* within the small mammal community with seasonal rainfall. The rocky sandstone country tends to have shallow soils, high run-off and is not prone to flooding during the wet season (Payne and Schoknecht 2011). Additionally, these areas are generally more protected from the degradation caused by cattle and are less perturbed by fire, hence may not be predisposed to change. Thus, the relative abundance of *Z. argurus* may remain more consistent, or at least follow a different trajectory over time when compared to the rodents inhabiting lower-relief areas.

5.3.1.11 Zyzomys woodwardi

Zyzomys woodwardi is endemic to the Kimberley region, including eight islands, and is restricted to the high rainfall areas (Begg 1981; Gibson and McKenzie 2012). This rodent species is thought to be patchily distributed, but locally common. It has shown preferences for rainforest patches on sandstone, open sandstone country with scattered low trees (such as *Owenia*, *Terminalia*, *Planchonia* and *Buchanania* spp.) over wattle shrubs and hummock grasses, and boulder strewn gullies and gorges (Kitchener *et al.* 1981; Bradley *et al.* 1987).

As discussed in Olds *et al.* (2016b [Chapter 2]) and Olds *et al.* (2016a [Chapter 3]), these habitat preferences overlap with those of *Z. argurus* and *D. hallucatus*. Spatial separation between *Z. argurus* and *Z. woodwardi* has been observed whereby *Z. argurus* has been recorded in habitat otherwise occupied by *Z. woodwardi* when the latter species is absent (Begg 1981). The prevalence of *Z. argurus* on both Doongan and Theda Stations suggests that *Z. woodwardi* is absent in these areas. However, the lack of survey effort in its favoured habitats may have limited the detection of *Z. woodwardi*. Similar to the other undetected species and given the penchants of *Z. woodwardi*, further targeted studies are required to confirm the absence of this species on Doongan Station.

5.3.1.12 Hydromys chrysogaster

The low numbers of *Hydromys chrysogaster* detected on Doongan and Theda Stations is likely a function of survey design. Trapping effort was not targeted at *H. chrysogaster* and, as noted in Olds *et al.* (2016b [Chapter 2]) and Olds *et al.* (2016a [Chapter 3]), it was not optimal for detection of this species. They are known to live in close proximity to water bodies, including both fresh and brackish water (Olsen 2008) and occur in a diversity of habitats throughout northern and eastern Australia (Atkinson *et al.* 2008; Speldewinde *et al.* 2013). Estimates of home range size are conflicting but findings concur that in riverine habitats this species remains close to the water and within riparian vegetation (Gardner and Serena 1995; Speldewinde *et al.* 2013). The trapping effort on Doongan and Theda Stations was likely to be on the periphery of their favoured habitat since traps were generally placed 10 m or more away from creeklines. This, considered in conjunction with their affinity for meat-baited traps (Laurance 1992), which were not used in this study, and their streamside foraging (Woollard *et al.* 1978), is likely to indicate this species went undetected. Given *H. chrysogaster* is considered stable in the NOK (Table 1) and across its range (Figure 6), there is little to suggest our low detection requires further investigation. However, future targeted studies of this species should carefully consider the trapping method and the location of the trap used.

5.3.2 Dasyuridae

5.3.2.1 Phascogale tapoatafa

Phascogale tapoatafa was not detected on Doongan or Theda Station. Only three individuals have been detected in the northwest Western Australia between 1997 and 2011 (Radford *et al.* 2014). One of these records is the most southerly Kimberley record of *P. tapoatafa*, which was found in 2002 at Yampi in *E. miniata* woodland (Palmer 2004). The status of *P. tapoatafa* is unclear due to the lack of recent records (Woinarski *et al.* 2014) but it is considered that recent range contractions have occurred in this region (Soderquist and Rhind 2008). It has been suggested that the northwestern *P. tapoatafa* populations be considered as endangered (Woinarski *et al.* 2014).

Phascogale tapoatafa is known to occur in a range of habitats, including woodlands, which were extensively surveyed in this study. Thus, no conclusion regarding lack of habitat can currently be drawn to explain its absence. However, individuals of this species can be difficult to detect using traditional survey methods such as Elliott and cage traps, and spotlighting, which were used in this study. The installation and monitoring of nest boxes may be a more efficient alternative for detecting *P. tapoatafa* in the future (Traill and Coates 1993). Hence, whether this species occurs on Doongan and/or Theda Station remains unresolved.

5.3.2.2 *Pseudantechinus ningbing*

Pseudantechinus ningbing occurs throughout the Kimberley and in the adjoining northeastern edge of the Northern Territory (Woolley 2008b). In the Kimberley, it has been recorded in rocky habitat, including both limestone (Woolley 1988) and sandstone (McKenzie *et al.* 1975a; Legge *et al.* 2008). In the Northern Territory, it has been associated with rugged dissected sandstone plateaus, including a rocky gully with a mixed woodland and a steep rocky scree within a gorge (Fisher *et al.* 2000).

The records on Doongan and Theda Stations were consistent with elsewhere in the NOK where *P. ningbing* has been recorded. *P. ningbing* is known to occur on MRNP and DRNP, as well as further south on Mornington Station (Central Kimberley). In the current study, across the broad habitats where *P. ningbing* was recorded, vegetation encompassed scattered trees to woodland sandstone communities, including *E. miniata*, *E. tetrodonta*, *Terminalia* spp., *Acacia* spp., *X. paradoxus* and *E. chlorostachys* with native grasses. There is very little known regarding the ecology of *P. ningbing* (Woolley 2008b). As suggested in Olds *et al.* (2016a [Chapter 3]), trapping effort in rugged habitats may have contributed to the detection of *P. ningbing* on Theda Station, however, further explanation of its lack of detection on Doongan Station would be speculative. Whilst there were too few records for inclusion in the community modelling in Olds *et al.* (in prep [Chapter 4]), these few records may be sufficient for a smaller scale investigation to be undertaken in order to help improve the knowledge of this species.

5.3.2.3 *Sminthopsis butleri*

Sminthopsis butleri is known from only one location in the NOK. This species was originally described from three specimens at Kalumburu, the northern most settlement in Western Australia. However, it has not been recorded there since its first detection in 1965 and 1966, >40 years ago (Woolley 2008a). The only other population occurs on the Tiwi Islands, Northern Territory, where it inhabits tall eucalypt (*E. miniata* / *E. tetrodonta*) forests. Beyond this, there is very little known about this species (Woinarski *et al.* 2014). Its lack of detection on Doongan and Theda Stations is consistent with the lack of detections elsewhere in the NOK. Given so few individuals are known and there is such a limited extent of occurrence (Woinarski *et al.* 2014), searching for *S. butleri* in the Kalumburu vicinity may yield extant populations and should be undertaken prior to the arrival of the cane toad.

5.3.2.4 Sminthopsis macroura

Sminthopsis macroura occurs in a variety of habitats, including hummock and tussock grasslands on sandy soils, cracking clays and stony plains (Morton and Dickman 2008). It has a wide distribution through most of central and northern arid-zone Australia, as well as the northern parts of Western Australia. Its range is on the periphery of the NOK (Figure 6). Records were found in the southern DRNP in 1899 by J. Keoyers and in other southern parts of the NOK by W.H. Butler in 1968 (DPAW 2015b). There may be other historical records that have not been published. Whilst the lack of detection of *S. macroura* on either Doongan or Theda Stations was unsurprising (Olds *et al.* 2016b [Chapter 2]; Olds *et al.* 2016b [Chapter 2]), its proximity in the historical records indicates the possibility of its occurrence and the potential presence of this species should not be excluded in future studies.

5.3.2.5 Sminthopsis virginiae

Sminthopsis virginiae was one of the most widely detected species on both Doongan and Theda Station. The detection of *S. virginiae* in all of the broad habitat types described in Olds *et al.* (2016b [Chapter 2]) and Olds *et al.* (2016a [Chapter 3]), as well as being associated with all of the land systems in Olds *et al.* (in prep [Chapter 4]), suggests that this species is a habitat generalist. *Sminthopsis virginiae* is thought to nest using dense vegetation such as thick grass or pandanus leaves (Woolley 2008c). Declines in abundance in northern tropical Australia have been related to the introduction of the water buffalo (*Bubalus bubalis*), which destroys dense pandanus thickets (Braithwaite and Lonsdale 1987). However, the replacement of pandanus stands with *Mimosa pigra* following buffalo intrusion, provided an impenetrable thicket which was thought to subsequently afford the protection that *S. virginiae* required. The decline in abundance of *S. virginiae* discussed in Olds *et al.* (in prep [Chapter 4]) as time since fire increased, may be related to longer-term subsequent changes in the grass layer following fire (Radford and Andersen 2012). With increasing time since fire, grass cover and richness tend to decrease, whilst upper and middle storey vegetation tends to thicken (Woinarski *et al.* 2004b). This supports the hypothesis that ground cover, or at least the resources it affords, is important for *S. virginiae* (Woolley 2008c) and that the elimination of this layer, albeit through cattle presence or habitat homogeneity, may impact on *S. virginiae* abundance (Price *et al.* 2005).

The presence of *S. virginiae* within the small mammal community during the months following fire is likely to relate to the life history traits of this species. Their oestrous cycle is around 30 days, with a 13-20 day pregnancy and suckling period of 65-70 days (Taplin 1980). Since these observations were based on laboratory and not field studies, it is uncertain whether the breeding cycle throughout the year that is observed in captivity is reflected in the wild. However, if they are continuous breeders, they may be able to recolonize areas following fire faster than seasonal breeding species. Information regarding home range and dispersal of *S. virginiae* is not currently known (Woolley 2008c). Additionally, *S. virginiae* is predominantly insectivorous, consuming large insects and occasionally small reptiles. Orthoptera have been shown to persist immediately following fire, presumably due to their ability to escape the fire itself, whereas most other invertebrates disappear (Radford and Andersen 2012). As such, sufficient food source may remain for *S. virginiae* post-fire and it may not be forced to migrate in search of resources. Investigation of the on-ground conditions where *S. virginiae* was detected would assist in demonstrating the importance of the ground layer.

5.3.2.6 Dasyurus hallucatus

Fifty-one of the sites surveyed on Doongan (Olds *et al.* 2016b [Chapter 2]) and Theda Stations (Olds *et al.* 2016b [Chapter 2]) were rugged sandstone or sandstone outcrops (over 12, 000 Elliott and cage trap nights), yet only fourteen *D. hallucatus* were detected. In contrast, Start *et al.* (2007) found *D. hallucatus* to be common at coastal and island sites in the NOK, where they recorded 236 *D. hallucatus* as a result of a similar trapping effort (10,917 trapnights) to that undertaken in the current study. This strongly indicates that sites on Doongan and Theda Stations do not support the high numbers observed in the national parks and, with only two records on Doongan Station, suggests that their distribution within the NOK is patchy (Hill and Ward 2010). The range of *D. hallucatus* historically extended across northern Australia, however, the eastern (Woinarski 1992a) and southwestern Kimberley (Start *et al.* 2012b) populations have severely declined, with this species now considered to have a discontinuous distribution across northern Australia (Hill and Ward 2010).

Two broad-scale environmental associations of *D. hallucatus* presence were shown in Olds *et al.* (in prep [Chapter 4]). Firstly, they were associated with the Buldiva land system, which is consistent with their preference for sandstone habitats. Secondly, *D. hallucatus* was absent when mean annual rainfall was less than 1100mm, yet there was no association with seasonal rainfall variation during the wet or dry seasons. Thus, the delineation of mean annual rainfall is likely to be a surrogate for another environmental variable, concurring with the pattern of loss from areas of low relief, with less mean rainfall, whilst persisting in the coastal and rugged areas in the NOK (Hill and Ward 2010). A complete explanation of their decline has yet to be ascertained. It has been attributed to a combination of fire, introduced species, disease and grazing regimes in Northern Territory, with presumably the same implications in the NOK (Woinarski *et al.* 2008; Woinarski *et al.* 2014).

5.3.2.7 Planigale maculata

Planigale maculata is currently recognised as the only *Planigale* species occurring within the NOK. However, there is some taxonomic uncertainty regarding the specific identities within this genus and it is likely that there are species complexes (Woinarski *et al.* 2014). Taxonomic investigation is currently being undertaken (K. Armstrong pers. comm.) to elucidate the planigale genus further. Records collected in the current study are being included in the taxonomic investigations. Qualitatively, two forms appeared to have been collected in the current study on Doongan and Theda Stations: those with a longer tail and those with a shorter tail. Two subspecies of *P. maculata* have been previously reported across their distribution (Jackson and Groves 2015), although there is limited support for these in the most recent analysis (Blacket *et al.* 2000; Woinarski *et al.* 2014). The earlier records from MRNP and DRNP were also identified as *P. maculata* (Kitchener *et al.* 1981; Bradley *et al.* 1987) and, following taxonomic revision, it would be beneficial to also substantiate the species occurrence both historically (from museum specimens) and with those currently present in these national parks.

Nevertheless, records of *P. maculata* from MRNP and DRNP were from low woodland over laterite, and shrubland over tussock grass with occasional sandstone outcrops (McKenzie *et al.* 1975b; Kitchener *et al.* 1981; Bradley *et al.* 1987). The records on Doongan and Theda Stations support these findings. Further description and analysis of the habitat of *P. maculata* here is redundant given the taxonomic uncertainty of this species. More complete description of the habitat of *P. maculata*, or the species/subspecies as eventually defined, should be carried out in light of the taxonomic revision. There is remarkably little known of its ecology despite *P. maculata* being considered to be common and widespread across the northern and eastern coasts of Australia (Burnett 2008).

5.3.3 Peramelidae

5.3.3.1 Isoodon auratus

Isoodon auratus was not detected on either Doongan or Theda Station. It was once distributed across more than 50% of mainland Australia (Woinarski *et al.* 2014), including the central deserts (Burbidge *et al.* 1988) and its range extended into New South Wales and Victoria (Ellis *et al.* 1991). This species still persists in the NOK and the Northern Territory, however these populations have also severely declined. The remnant populations are now known from isolated localities along the NOK coastline (including MRNP and PRNP (McKenzie *et al.* 2008)), four islands in the NOK (Lachlan, Augustus, Storr and Uwins Islands (Gibson and McKenzie 2012)), two islands in the Pilbara (Barrow and Middle Islands) and one island in the Northern Territory (Marchinbar Island (Woinarski *et al.* 1999b)).

Historically, it occupied a wide range of habitats, including hummock and tussock grasslands on sand-dunes and sand-plains in the arid zone, Acacia and Eucalyptus woodlands in the tropical semi-arid zone, and vine thickets, heath and woodland in rugged sandstone and volcanic country in the subhumid tropics (McKenzie *et al.* 1975a; Southgate *et al.* 1996; Palmer *et al.* 2003). The main causes of decline are considered to be predation by feral cats and inappropriate fire regimes, particularly large-scale fire (Woinarski *et al.* 2014). Recent evidence from hair analyses of predator scats collected on Theda Station have indicated that *I. auratus* may be present (R. Palmer pers. comm.). However, as suggested in Olds *et al.* (2016b [Chapter 2]) and Olds *et al.* (2016a [Chapter 3]), Doongan and Theda Station may have limited habitat that provides sufficient protection required for *I. auratus* to persist. Nevertheless, targeted survey effort, including using other survey techniques such as predator scat analysis or remote camera surveys (Turpin 2015), may further elucidate this species' occurrence.

5.3.3.2 Isoodon macrourus

The habitat in which *I. macrourus* was recorded on both Doongan and Theda Stations, was consistent with findings elsewhere within the NOK region (Bradley *et al.* 1987; Kemper *et al.* 1990) and across this species' range in northern Australia (Gordon 2008). This omnivorous species prefers grasslands, woodlands and open forest, where there is reasonable ground cover (Friend and Taylor 1985; Vernes 2003). There is evidence of decline in *I. macrourus* populations in northern Australia, thought to be predominantly due to the presence of cattle and altered fire regimes (Fitzsimons *et al.* 2010).

Whilst *Isoodon macrourus* is considered to be sensitive to fire (Pardon *et al.* 2003), conflicting results have been found regarding its response to both time since fire and fire frequency (Pardon *et al.* 2003; Firth *et al.* 2006; Olds *et al.* in prep [Chapter 4]). The most consistent finding is a preference for sites that are exposed to fine-scale low intensity fires (Firth *et al.* 2006). However, it has also been found to avoid sites with frequent extensive fire and sites with complete fire exclusion (Firth *et al.* 2006). In Olds *et al.* (in prep [Chapter 4]), it was found to have a bimodal response: present within the small mammal community up to 24 months since fire and again 120 months after fire. This may to some extent explain the variability found in other studies. However, it contrasts with findings in the Northern Territory where *I. macrourus* was absent at sites with complete fire exclusion (Firth *et al.* 2006). Furthermore, the temporal impacts of fire regimes have been shown to negatively affect the survival of *I. macrourus*. *Isoodon macrourus* was driven to local extinction across a 5 year fire experiment, though to be the result of both direct mortality and emigration (Pardon *et al.* 2003). However, unburnt sites also reflected this decline, and it was proposed that the vegetation homogeneity found in unburnt sites was also unfavorable for this species (Pardon *et al.* 2003). This indicates that there are comparable habitat attributes in both fine-scale low intensity burning and long-term unburnt patches that *I. macrourus* utilised. Long unburnt patches in the Northern Territory have been found to resemble rainforest vegetation after fire exclusion (for 23 years) (Woinarski *et al.*

2004b). This variation in response indicates that *I. macrourus* is likely influenced by floristic and vegetation structural attributes, which are influenced by broad-scale environmental factors, such as fire.

Isoodon macrourus is generally considered to be a solitary animal. However, the relative abundance of *I. macrourus* during some of the site surveys on Doongan and Theda Stations suggests the species can occur in high densities given suitable conditions. When detected during site surveys, few individuals were captured, as might be expected within a 50x50m area for an animal of this size and with a home range of 1-6 hectares (Gordon 1974). However, there were sites in which this pattern was not observed, and in fact, *I. macrourus* was trapped in much higher numbers. These included a rainforest site, where eleven individuals were recorded, and several basalt sites where high *R. tunneyi* abundance was also observed. This indicates that where habitat and food resources are adequate, they are able to co-exist in higher numbers.

The positive association of rainfall during the wet season prior to trapping, in conjunction with its response to fire, suggests that landscape productivity is important for *I. macrourus*. This is further supported by the co-existence demonstrated in the Napier land systems, which are more nutrient rich. The interaction of these environmental variables suggests a complexity in *I. macrourus* presence that, without investigation of on-ground attributes, cannot be deciphered further in the current study.

5.3.4 Macropodidae

5.3.4.1 Petrogale burbidgei

The distribution of *P. burbidgei* is confined to the north-west coast of the NOK, where it has been recorded in rugged, dissected King Leopold Sandstone (Start *et al.* 2007; Pearson *et al.* 2008; Corey *et al.* 2013). There is little known of its ecology beyond its presence where there is adequate shelter (Pearson *et al.* 2008). It is currently known from less than 10 locations, including sites within MRNP and PRNP (Start *et al.* 2007; Woinarski *et al.* 2014). Doongan and Theda Stations are east of its current known distribution and may not possess the highly fractured sandstone this species is considered to prefer.

5.3.4.2 Petrogale concinna

Petrogale concinna is confined to rocky slopes with rugged boulders, caves and crevices, in the higher rainfall regions of the Northern Territory and the Kimberley (Churchill 1997; Sanson and Churchill 2008). These populations are currently recognised as three subspecies: *P. c. monastria* (Kimberley, Western Australia), *P. c. concinna* (Victoria River District, Northern Territory) and *P. c. canescens* (Top End, Northern Territory) (Woinarski *et al.* 2014). There has been decline recorded in the Northern Territory (Churchill 1997) but the status of the Kimberley population has not been established (Woinarski *et al.* 2014). They have been recorded in DRNP (Start *et al.* 2007), which suggests that, unlike *P. burbidgei*, they are not confined only to the coast and it is likely that they historically occurred, and potentially still currently occur, on Doongan and Theda Stations. Rock-wallabies have indeed been detected on Doongan and Theda Stations as part of the broader survey effort, but the genetic analyses of these showed that all samples were *P. brachyotis* (Potter 2011).

5.3.5 Pseudocheiridae

5.3.5.1 Petropseudes dahli

Petropseudes dahli is a specialised possum that lives exclusively in rocky outcrops throughout the Kimberley and northern parts of the Northern Territory (Figure 6) (Webb *et al.* 2008). This species is dependent upon rocky habitat for shelter and, unlike most possums, it does not build a nest but sleeps in rock crevices. Although the rock outcrops inhabited by *P. dahli* are typically sandstone, they vary in size and resource quality (Runcie 2002). *Petropseudes dahli* has been observed to have a folivorous diet, feeding on plant species detected on both Doongan and Theda Station. On Theda Station, the rugged sandstone sites where *P. dahli* were detected, supported vegetation that they are known to feed on including *Acacia* spp., *Eucalyptus miniata*, *Terminalia* spp., and *Erythophleum chlorostachys* (Runcie 2002).

Petropseudes dahli was detected more frequently on Theda Station than on Doongan Station. However, a greater trapping and spotlighting effort was undertaken in both rugged sandstone and sandstone outcrop on Theda Station, which would have increased the likelihood of detection of this species. Along with this, the rugged sandstone surveyed on Doongan Station may not afford the same complexity, or other habitat characteristics, which were not evaluated in this study. The limited number of detections in this study were not sufficient to support further habitat analyses, and spotlight survey data were excluded from modelling in Olds *et al.* (in prep [Chapter 4]). Future studies of the occurrence and habitat preference of *P. dahli* would benefit from including measures of rock characteristics, such as crevice depth and density, as is being undertaken for a study on *Wyulda squamicaudata* (Hohnen *et al.* 2015a).

5.3.6 Phalangeridae

5.3.6.1 Trichosurus vulpecula

Trichosurus vulpecula occurs across much of Australia, however, its taxonomy has not been fully resolved and there a number of subspecies currently recognised (Kerle *et al.* 1991). The north western subspecies is patchily distributed and is known to occur from the Kimberley through to the Gulf of Carpentaria (Northern Territory) (Woinarski *et al.* 2014). There has not been a robust estimate of the population size of *T. vulpecula* in northern Australia (Woinarski *et al.* 2014). Furthermore, its status in the NOK is unknown as there are too few records (Start *et al.* 2007; Start *et al.* 2012b; Corey *et al.* 2013) to enable any change in occurrence to be determined (Woinarski *et al.* 2014). It is nevertheless considered to be undergoing decline across much of its range and it has rarely been sighted in the NOK in recent years (Woinarski *et al.* 2014). It cannot be ascertained if the lack of detection of *T. vulpecula* on Doongan and Theda Stations is significant, nor whether it was historically present on these stations and is now absent, nor if it has always been present at low abundance and has gone undetected in this study.

5.3.6.2 Wyulda squamicaudata

Wyulda squamicaudata is restricted to rocky habitats in northern Western Australia. Until recently it was thought to have only persisted in the NOK, but it has been rediscovered further east, in the Cockburn Ranges (Doody *et al.* 2012). A recent study found there is little genetic differentiation between the eastern and western populations (Potter *et al.* 2014). It is suggested that *W. squamicaudata* persists in refugia, and that niche differences and localised adaptations may have occurred in the eastern population (Potter *et al.* 2014). In the NOK, it is known to persist in the MRNP and PRNP (Start *et al.* 2007) and in the

Artesian range (Hohnen *et al.* 2015a). This species dens in deep rock crevices and emerges at night to forage (Burbidge and Webb 2008). It feeds on plant species detected on both Doongan and Theda Stations (such *as Xanthostemon* spp. and *Planchonia careya*) and has been found to be sympatric with *P. dahli*, although it is likely they compete for shelter and resources (Runcie 1999). The detection of *P. dahli* indicates that *W. squamicaudata* may be present but has been elusive on Doongan and Theda Stations.

5.3.7 Petauridae

5.3.7.1 Petaurus breviceps

Petaurus breviceps is considered to be a widespread species in Australia, including northern, eastern and southern Australia (Figure 6). The sightings on Doongan Station were opportunistic, which meant these detections were not within surveyed quadrats, and no habitat information was ascertained. The captures on Theda Station provide limited information, but supported general observations that *P. breviceps* occurs in woodlands where it utilises tree hollows for shelter. This species occurs at low density in northern Australia (Suckling 2008) and has not been frequently detected in the NOK (DPAW 2015b), hence the limited number of detections in this study is not surprising despite significant spotlighting effort across the two stations. It should be noted that in northern Australia it is currently a subspecies classified, *P. b. ariel,* although recent taxonomic work has shown the northern populations are likely to be separate species, and possibly more closely related to *P. norfolcensis* and *P. gracilis* than to the *P. breviceps* in eastern and southern Australia (Malekian *et al.* 2010).

5.4 Habitats and drivers of change

5.4.1 Broad habitats and land systems

Fourteen broad habitat types were described for Doongan and Theda Stations (Appendix 1 and Figure 14). The habitats found on these stations have not been described previously. These descriptions provide relevant context for the area in which this study was undertaken and, more broadly, in relation to the habitat present within the NOK. Broad habitat classifications are a widely used tool with similar descriptions of habitat types used in the three adjacent national parks, MRNP, PRNP and DRNP (Kabay *et al.* 1975; Miles *et al.* 1975; Kitchener *et al.* 1981).

The 14 broad habitat types described for Doongan and Theda Stations provide general descriptions of the underlying geology, vegetation and soil. They are more descriptive than the land system classification as they take into account land form, i.e. the position of the habitat within the surrounding landscape and the type of terrain. For instance the Pago land system in Olds *et al.* (in prep [Chapter 4]) encompasses the sandstone outcrop, sandstone plain and sandstone riparian formation habitat types described in Olds *et al.* (2016b [Chapter 2]) and Olds *et al.* (2016a [Chapter 3]). The inclusion of broad habitats types in the modelling methods in Olds *et al.* (in prep [Chapter 4]) was not possible due to too many habitat categories. Nevertheless, the results in Olds *et al.* (2016b [Chapter 2]) and Olds *et al.* (2016a [Chapter 3]) suggest that the broad habitats provide some guidance as to the areas in which the small mammal species are likely to occur. The identification of the broad habitat types may be particularly useful for researchers undertaking on-ground work. Given that land system was identified as a potential predictor of species presence in Olds *et al.* (in prep [Chapter 4]), further investigation of the correlation between the broad habitats, land systems and species occurrence may help identify priority areas for both conservation and undertaking further explorative surveys. Locations of interest could be identified spatially using desktop analyses and thereafter targeted using on-ground broad habitat attributes.

5.4.2 Rainfall

Rainfall gradient is thought to influence species diversity in northern Australia (Woinarski *et al.* 1999a). In the NOK, higher rainfall areas tend to support a higher richness of species, often in higher abundance, than those found in the lower rainfall counterparts (Olds *et al.* 2016b [Chapter 2]). However, a range of complex interactions between rainfall and the landscape exist. The mechanisms determining the influence of rainfall in the NOK are yet to be clearly deciphered.

Rainfall in the NOK has contributed to the weathering of the land surfaces (Williams and Sofoulis 1967; Petheram *et al.* 2003). The structure of the surface topography is largely determined by the underlying geology and lithology (Pepper and Keogh 2014). Similarly, the presence and structure of drainage basins, rivers and creeks are controlled by the underlying geology. The effect of rainfall and weathering processes is variable on different substrates and this variability has contributed to the heterogeneity of the NOK land forms.

Figure 14. Broad habitat types surveyed on Doongan and Theda Stations in the Northern Kimberley.

Habitats types: a) blacksoil, b) laterite flats, c) laterite volcanic hills, d) lateritic creekline, e) monsoon forest, f) rainforest, g) rugged sandstone , h) sandstone outcrop, i) sandstone plains, j) sandstone riparian formation, k) volcanic hills, l) volcanic low woodland, m) volcanic riparian formation, n) wetland. Broad habitat types described in Appendix 1.

Figure 14. Continued.

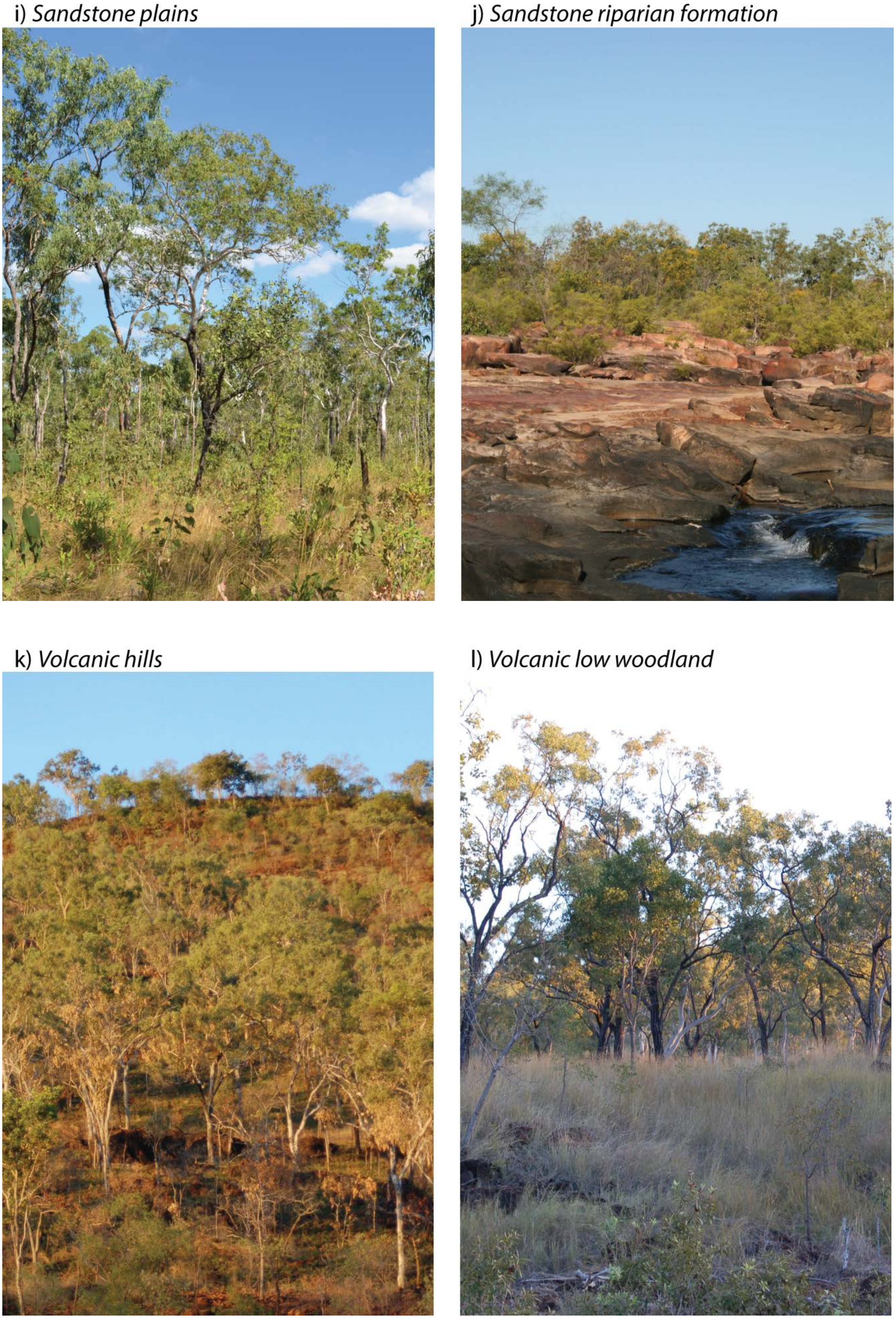

Figure 14. Continued.

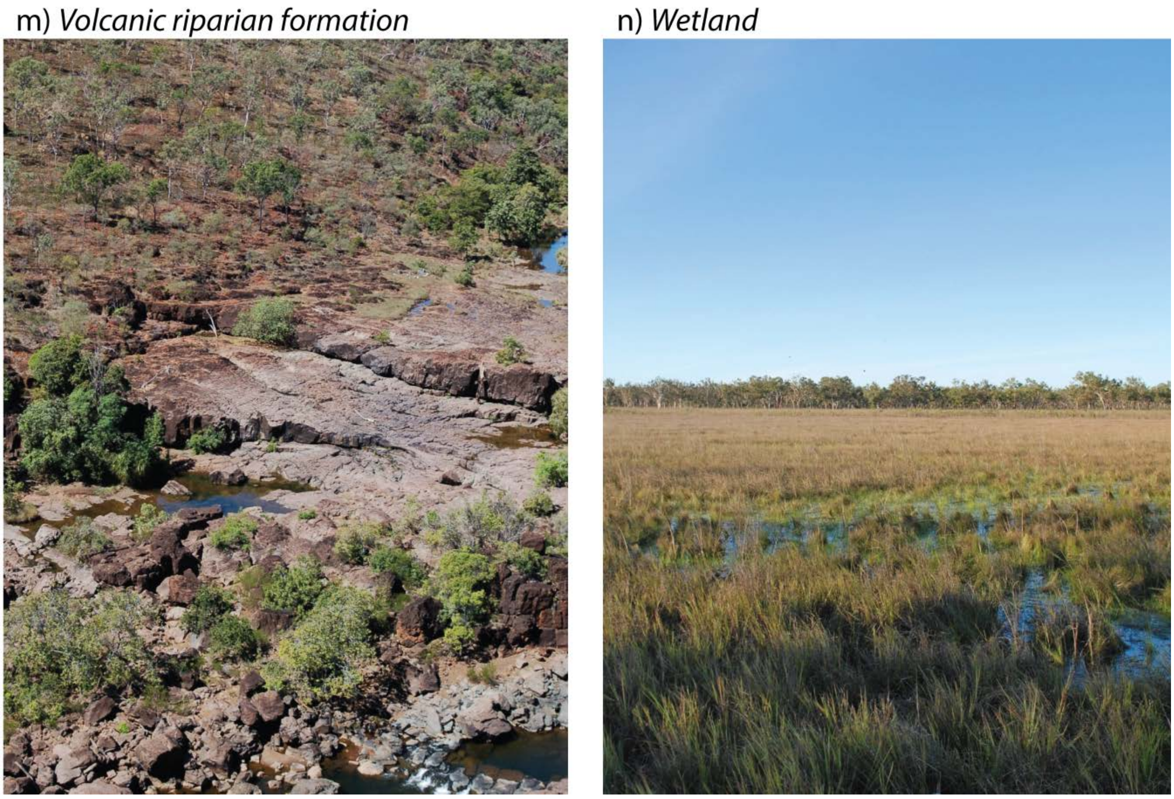

Figure 14. Continued.

Substrate composition, in conjunction with water accessibility, is thought to be the primary cause of different vegetation patterns (Woinarski *et al.* 2007; McKenzie *et al.* 2009). Water availability influences plant species' ability to grow, seed and reproduce. Plants vary in both their utilisation of, and requirements for, different water resources. As such, species may respond to differences in rainfall, accumulation in low-lying areas and root access to groundwater. There is additional complexity created by soil moisture being inherently linked to topography and underlying geology (Pepper and Keogh 2014). As such, plant distributions have been found to be strongly associated with the moisture gradients associated with topography and soil type and/or texture (Parker 1991; Fayolle *et al.* 2012). Rainfall created changes in vegetation structure and composition (Madsen and Shine 1999), and thus resource availability and shelter attributes, are ultimately likely to affect small mammal species presence and relative abundance.

Rainfall may also influence the burning patterns and the intensity of fire in the landscape. Higher moisture areas support greener vegetation, which is subsequently less disposed to burning (Woinarski *et al.* 2007). As such, greener vegetation patches are likely to be less severely affected by fire. However, there are further complicating feedback mechanisms occurring. Fire causes drying of the surface and increases soil moisture evaporation (Woinarski *et al.* 2007). This likely influences the structure, survival and suitability of vegetation as both resources and habitat for the small mammal community. Furthermore, there may be also immediate physical impacts on species' abilities to inhabit areas during rainfall periods. For instance, significant rainfall events may cause populations to migrate to seek shelter, protection and higher ground. This would likely be the case for species such as *R. tunneyi* and *P. delicatulus*, whose burrows may be inundated and destroyed during heavy rainfall, rendering them uninhabitable.

Across the study period, there was spatial variation in the amount of rainfall across Doongan and Theda Stations. This variation was often >500mm during the wet seasons (Figure 15). Additionally, the scale of rainfall variation was spatially different across years. For instance, in 2010-2011 the lowest rainfall (1950 mm) was in the northeast, whilst the highest rainfall (2700 mm) was in the west (Bureau of Meteorology 2014). Contrastingly, in the 2013-2014 wet season the lowest rainfall (1200 mm) was in the southeast, whilst the highest rainfall (1500 mm) was in the northwest of the stations (Figure 15). This variation would have created site specific differences in both the amount of rainfall experienced during each season and the variation exhibited across years. Subsequently, this would have influenced the site specific responses of the small mammal community. It would be interesting to compare the rainfall variation with local habitat variation, to see if there is a clear relationship.

It has been suggested that the association of ground water and rainfall, and subsequently small mammal response, operates on an eight year time-scale (Braithwaite and Muller 1997). The results in Olds *et al.* (in prep [Chapter 4]) support the existence of a time-lag in small mammal response, however, it appears to be on a smaller time-scale than that previously suggested. However, more than four year was not tested in this study and extrapolating the data further may provide additional details. Nevertheless, there appears to be a cumulative effect of rainfall. It appears that the rainfall during the wet season compensates for the conditions during the dry season, and that the wet season provides a period of regeneration. However, the influence of exceptionally high rainfall may not be immediate and regeneration may occur across multiple years. Such has been observed in tropical Queensland, whereby some Eucalyptus species took multiple wet seasons to recover following low rainfall conditions (Fensham and Holman 1999). This is similarly the case, albeit more eruptive, with small mammals in the arid regions (Dickman *et al.* 1999b; Letnic *et al.* 2005; Letnic and Dickman 2010). Water sources become depleted during times of lower than average rainfall. High rainfall events may replenish ground water resources, such as aquifers, with the effect of replenishment being influential over a greater period of time than the immediate season, enabling vegetation change restoration to occur over a number of years.

The length of the wet season may also be influential (Woinarski *et al.* 2007). In Olds *et al.* (in prep [Chapter 4]), the number of days in which rain fell was included in the original variables considered for modelling. However, these were excluded from the final models produced as they were not suitable due to collinearity with other rainfall variables. In the NOK, the timing of both the onset and the conclusion of the wet season is highly variable (Shi *et al.* 2008). Investigation of the influence of both the onset and the length of the wet season on the small mammal community may disseminate additional relationships not considered in this study. Similarly, the length of the dry season should be considered in future investigations. Rainfall during the dry season may reduce the severity of the conditions and enable some replenishment of water resources, albeit minor.

The influence of the various aspects of rainfall are likely to affect each of the small mammal species differently. For instance, *I. macrourus* may be associated with the retention of ground water in promoting growth and survival of herbaceous and shrubby species. Conversely, heavy rainfall in the wet season prior to trapping may have a negative effect, as was found in Olds *et al.* (in prep [Chapter 4]), for burrowing species such as *R. tunneyi* due to the aforementioned landscape inundation. Whilst this is to some extent speculative, it would be useful to investigate the different rainfall variables for each species, beyond that undertaken for the community in Olds *et al.* (in prep [Chapter 4]). This may help elucidate the species specific responses and more fully describe the mechanisms of rainfall's influence.

Nevertheless, the current study supports rainfall being a key driver in the NOK. However, it is clear there is a level of complexity that needs to be taken into account when considering its effect. The diversity of habitats, capacity for water retention, presence of ground water, and spatial variability contribute to creating a heterogeneous rainfall landscape (Woinarski *et al.* 2007). This variation creates a mosaic of conditions across the NOK. Additional annual variability is created by the different temporal rainfall patterns.

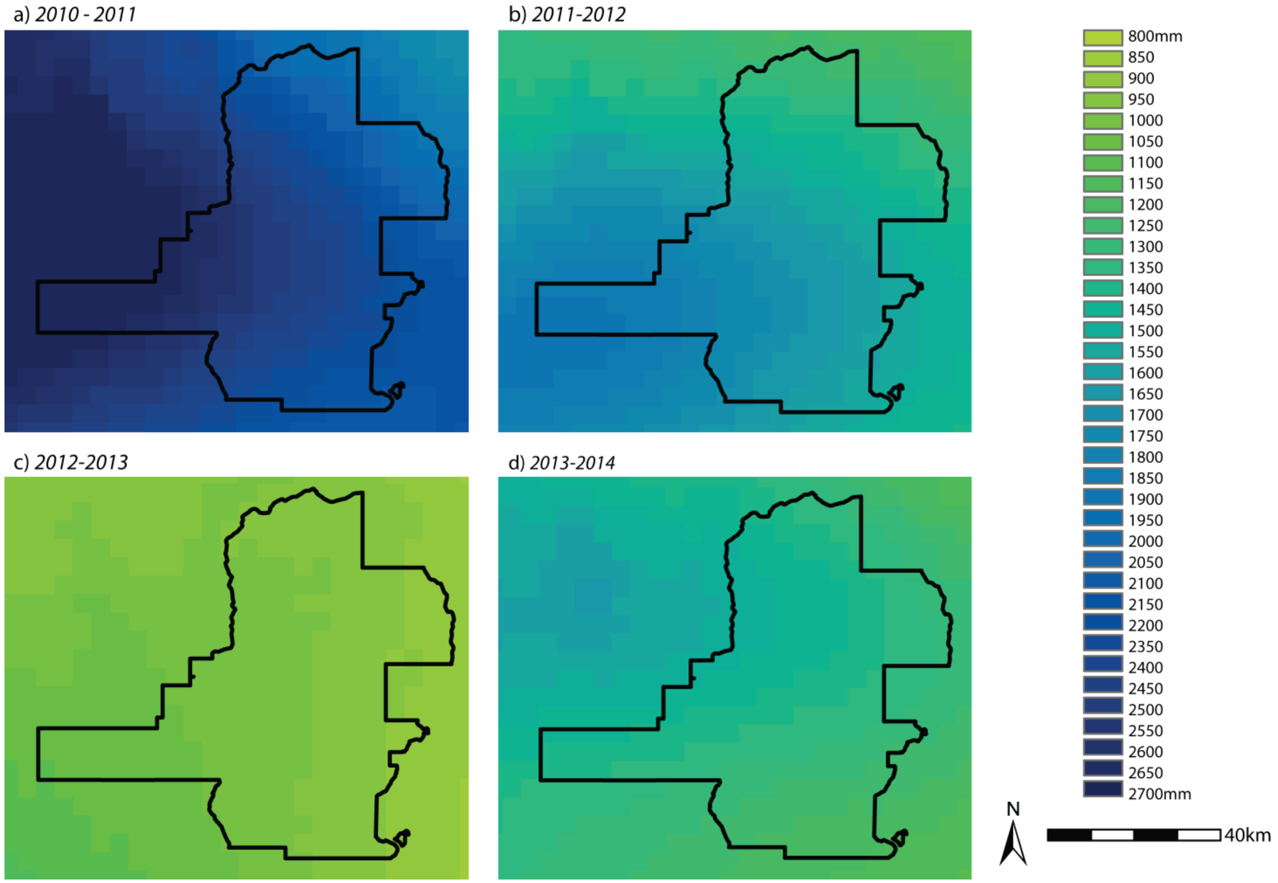

Figure 15. Rainfall occurring during the wet seasons (October to April) in a) 2010-2011, b) 2011-2012, c) 2012-2013 and d) 2013-2014.

Gradient indicates millimeters measured. Black outline shows combined boundary of Doongan and Theda Stations. Original data from Bureau of Meteorology (2014).

5.4.3 Fire

Fire is a common element of the NOK environment. Historically, low intensity, small-scale fires across the region were used in traditional aboriginal burning practices (Dyer *et al.* 2001). These are thought to have created a mosaic effect of patchy burns with vegetation of different ages (Dyer *et al.* 2001). However, fire regimes have changed dramatically due to European influence. There is now a propensity for hot, intensive, broad-scale, late-dry season fires (Radford 2010; Russell-Smith *et al.* 2003b). Fisher *et al.* (2003) estimated the extent of fire in the NOK between 1990 and 1999 as burning 23,134km^2, including parts of Theda Station. This equates to approximately 31% of their study area being burnt annually. The authors suggest that this is comparable to, albeit lower than, the Northern Territory estimates of approximately 40% to 56% in various regions. The authors also suggest that such patterns are likely to have similar deleterious effects to those observed in the Northern Territory, on both the vegetation and the habitats (Fisher *et al.* 2003). In recent years, approximately 50% Doongan and Theda Stations has burnt annually with some fires occurring late in the dry season (North Australian Fire Information (NAFI); http://firenorth.org.au).

Late dry season fires may have a greater impact on vegetation and fauna than those ignited early in the dry season (Williams *et al.* 1998). Vegetation becomes drier as the dry season progresses and subsequently burns late in the season tend to be hotter (Williams *et al.* 1998). These hotter burns scorch the vegetation, including the canopy (Williams *et al.* 1998; Dyer *et al.* 2001). Ignition of late season fires is not under the control of land managers, and may be started by lightning strikes, passing tourists and/or local community members travelling through the stations. The timing of fires was not investigated in the present study. Further investigation of the potential impact of late, compared to early, dry season fires is important for teasing out the fire-related findings reported in Olds *et al.* (in prep [Chapter 4]).

Despite being recognised as an important aspect of land management, albeit agricultural or ecological, there is limited literature available on the impact of fires on both fauna and flora within the NOK region. However, there is clear evidence that fire influences vegetation in northern Australia (Fisher *et al.* 2003; Williams *et al.* 2003; Vigilante *et al.* 2004; Vigilante and Bowman 2004a; Vigilante and Bowman 2004b; Andersen *et al.* 2005). Structural damage, predominantly due to fire in conjunction with cattle disturbance, has been observed in rainforest patches in the NOK (McKenzie and Belbin 1991). However, there remains a myriad of interrelated unknowns regarding the influence fire has in the NOK generally (2010) and particularly for small mammals (Radford *et al.* 2015; Griffiths and Brook 2015; Griffiths *et al.* 2015).

The findings in Olds *et al.* (in prep [Chapter 4]) support fire as having affected the small mammal community, although the precise mechanisms for its influence could not be ascertained. Further investigation, and particularly detailed comparisons, of vegetation condition and habitat attributes in relation to fire may improve our knowledge of its influence on on-ground changes. Subsequently, the influence of these changing conditions may help explain the associations found with small mammal presence and relative abundance. Legge *et al.* (2008) predicted that small mammal populations would be extirpated should regular, extensive and intensive fires persist across the landscape. The findings in Olds *et al.* (in prep [Chapter 4]) suggests there is a period where small mammal richness is favoured (6-48 months) and that the maintenance of a range of fire-age classes would be most beneficial to provide varying heterogeneity requirements of the different species. The findings in Olds *et al.* (in prep [Chapter 4]) indicated that the use of fire should promote areas that are unburnt, as opposed to creating burnt habitat, as previously suggested by Radford (2010).

Currently, management practices have been put in place as an immediate measure to mitigate potential fire related declines in the NOK (Legge *et al.* 2011b). However, fire-related conservation and the outcomes of management practices require more extensive investigation than there is currently available in the literature. The prevention of extensive hot burns, which the current burning programs are intended to achieve, appears to be a consistent aim. However, the diversity of responses and the influence of fire in creating variation indicate that an all-encompassing blanket management approach using a single regime may disadvantage some species in the small mammal community. Nevertheless, a collaborative effort towards fire management across the NOK region, such as that undertaken by the EcoFire program, of which Doongan and Theda Stations are part (Legge *et al.* 2011b; Skroblin *et al.* 2014), should be pursued to support wide-scale conservation effort. However, in doing so, the difference between a collaborative management approach and a sole regime should not be confused.

5.4.4 Introduced Species

There are other factors that likely influence the small mammal community on Doongan and Theda Stations. For instance, the presence of feral cats (*Felis catus*). Feral cats are cryptic in nature and their prevalence on the stations and across the NOK is not currently known, although they have been detected on both Doongan and Theda Stations (C. Myers unpublished data). Feral cats are post-fire opportunists (McGregor *et al.* 2014) and a recent study has shown they may be having a greater impact in the Kimberley region than was previously thought to be the case (Frank *et al.* 2014). Although the density and abundance of cats in northern Australia remains largely unquantified, land management activities have been found to favour higher cat densities (McGregor *et al.* 2014). Land management is also likely to have favoured the other major vertebrate pest in northern Australia, the cane toad (*Rhinella marina*), through its preferential use of cleared vegetation for dispersal (Brown *et al.* 2006). The cane toad was not present on Doongan or Theda Stations during the current study, but it is expected to invade the area within the next year or so (DPAW 2015a). The findings in the current study will provide important baseline information for monitoring potential change as a result of the presence of these species.

Although there has been limited research into the impacts of pastoralism on fauna (Woinarski 1999), there is growing evidence of the deleterious effect of livestock in northern Australian (Fitzsimons *et al.* 2010). A quantitative measure of cattle impact was collected during the environmental assessments undertaken during this study. However, it proved to be unsuitable for use in the modelling in Olds *et al.* (in prep [Chapter 4]). Unfortunately this limited the comparison of cattle with the small mammal community to the qualitative association discussed in Olds *et al.* (2016a [Chapter 3]). However, evidence from elsewhere indicates that cattle influence the distribution and abundance of small mammal species. On Mornington Sanctuary, in the Central Kimberley, mammal abundance doubled after destocking a 40,000 ha fenced area, with relatively small native rodents and dasyurids demonstrating positive responses post-removal (Legge *et al.* 2011b). Studies in arid and semi-arid northern Australia (Fisher 1999; Landsberg *et al.* 1999) demonstrated that the impacts of pastoralism on vegetation were concentrated around water sources, whilst Woinarski and Ash (2002) found that pastoralism is at least partly responsible for broad-scale changes in biodiversity. Localised damage caused by cattle presence in riparian areas has been further shown to impact on the vulnerable purple-crowned fairy-wren (*Malurus coronatus*) populations, including in the NOK (Skroblin and Legge 2012; van Doorn *et al.* 2015).

Much like fire, the denudation caused by cattle may vary depending on seasonality. For instance, defoliation of the kangaroo grass (*Themeda triandra*) early in the wet season over a number of years inhibited the species' ability to successfully develop tillers, whilst grazing in the dry season had little effect as the grass was senescent (Ash and McIvor 1998). Changes such as these are likely to influence the habitat suitability and resource availability for small mammal species. Although speculative, the decline of both *R. tunneyi* and *S. virginiae* within the community as time since fire increased may be related changes in resource quality and availability. Grass tissue quality and biomass changes have been found to decrease with increasing time since fire (Lewis 1984; White 1993; Stiling *et al.* 1999; Radford and Andersen 2012); a similar effect may also be created by grazing.

5.5 Knowledge gaps

Whilst there was variation shown in the responses of small mammal species to land system, fire and rainfall, the mechanisms and implications for both the community and individual species has yet to be fully deciphered. Continuing to gain knowledge about the small mammal fauna of the NOK is particularly important given there is an extinction crisis feared for northern Australia, with trends indicative of many small native mammals undergoing decline (Fitzsimons *et al.* 2010; Woinarski *et al.* 2011a). The low trap success of the small mammals in the current study has yet to be fully explained, and it is not known whether this was 'normal' or, as is more likely to be the case, reduced from past levels of presence and relative abundance. Ongoing monitoring of these species is important for evaluating future changes, whether deleterious or positive.

The ranges of the large-bodied arboreal rodents, bandicoots and *D. hallucatus* in the NOK already appear to be restricted to the high rainfall areas (Radford *et al.* 2014). Heterogeneous refuge areas will likely form a valuable stronghold for these species in this region in the future. Identification and surveillance of additional structurally complex sites, monsoon forests and vine thickets in the NOK would be beneficial. As the stations are very large, and most areas inaccessible, there may be important, as yet unknown, refugial patches that currently support a high biodiversity (Pepper and Keogh 2014). New species of lizards, snails and plants continue to be detected in the NOK (Doughty 2011; Kohler 2011; Oliver *et al.* 2012; Maslin *et al.* 2013) and these hidden refuges may have more to be revealed yet.

Conversely, there were a number of species identified in this study, such as *L. lakedownensis*, *P. delicatulus* and *S. virginiae*, that were detected more frequently than has been found in the adjacent national parks (Start *et al.* 2007; Corey *et al.* 2013). It is important to recognise that, although the savannas may not be as visually appealing, attractive to tourists, or offer the extensive refuges of the more coastal areas, these savanna areas should not be overlooked in conservation planning. The savanna is perhaps the first place to be affected and degraded by ineffective land management practices, and could act as a cursory indicator for the wider condition of the landscape.

It is important that as scientific data come to hand, they be shared with land managers and with community members that have planning responsibilities. There is a need for consolidated management practices and research methods in the NOK. Research techniques in northern Australia have been gradually employing similar methods (Woinarski *et al.* 2004a; Price *et al.* 2005; NRETAS 2011; Corey *et al.* 2013; Radford *et al.* 2014). In the current study, changing from exploratory transects (2006/2007) to quadrats (2008 - 2014) more closely aligned the survey method with those being undertaken across the region. Consolidating methods was the key motivation for this change, in order to increase both the usefulness of the information obtained and its comparability to other studies.

New statistical methods, such as those used in Olds *et al.* (in prep [Chapter 4]), are allowing investigation using spatial-scale modelling. However, basic ecological information and occurrence records are becoming less frequently published. Large scale modelling is increasingly becoming a popular desktop tool. However, the results are only as good as the weakest data being investigated, and the collection of field data still provides an essential service for assessing biodiversity and its potential changes (Price *et al.* 2010). The conflicting results for some of the variables across both the NOK and northern Australia suggest that there may be fine-scale detail in the small mammal species' requirements that are not taken into account in broad-scale environmental assessments (Di Stefano *et al.* 2011). Investigation into the quality and conditions of habitat at a site scale would improve our knowledge of both the specific requirements of the particular species and of their correspondence with spatial variables.

Whilst cost is often prohibitive for investigating such remote and inaccessible areas, improved knowledge of the small mammal fauna would greatly increase the capacity to undertake effective management activities. There is a need for further investigation using regionally consistent study methods, to establish baseline information and to improve our knowledge of the small mammal fauna. At the present time many aspects of both the NOK and its fauna are poorly understood and have received little, or even no, research attention to date. A more comprehensive list of reserach questions is described below (Future Research), with key areas of recommended future investigation to include:

- Biodiversity value of pastoral land as intermediaries or corridors between national parks,
- Environmental relationships of some of the lesser known species to determine their habitat requirements,
- Targeted surveys to search for the rare and potentially highly vulnerable species,
- Impact of disturbance, including the prevalence of fire, cattle and cats, particularly on localised and rare small mammal species.

5.6 Future research recommendations

For many species and locations, there is no baseline data against which to measure or detect changes in species' distribution and abundance. This extends to the presence of introduced species, which is particularly imperative as the cane toad distribution is now extending in the NOK region (DPAW 2015a). Improved communication between research programs would facilitate broader understanding across northern Australia. Access to data (or information) is limited by the availability of the information and access to unpublished results are not forthcoming. The establishment of a standard set of environmental indicators and criteria would enable regional research to be undertaken. These standard procedures could then be applied across lands of different tenure and increase the comparability of the data. Knowledge gaps reduce the efficacy of strategies to be developed for ameliorating, or at least building resilience to, imminent threats. Systematic biodiversity surveys of the whole region and collaboration utilizing currently available data sets should be used to establish a better understanding of small mammal status, environmental associations and landscape health.

A wide range of research questions should be undertaken in the future to help inform appropriate management actions. A comprehensive list of recommended research questions would be extremely numerous. However, research priorities should focus on establishing basic information on individual species, such as their life history, along with investigating the potential major drivers of change.

5.6.1 Life history and population structure

At the present there is little known about the life history of most of the NOK species. The challenges faced in undertaking surveys in the NOK during different times of the year, particularly during wet periods, has limited the information currently available, with most data gathered during the dry season. Similarly, the status of and/or changes in genetic diversity for small mammal species across the region is little known. This is needed to enhance our understanding of the small mammal populations and their structure, genetic diversity, and subsequent application of management activites that may be required. Additionally, the movement and dispersal of the small mammal species in the NOK has received little attention. Management strategies need to be informed by knowledge and hence research in order to treat populations appropriately. There are many assumptions of the movement patterns and how species use the landscape but these need to be tested and investigated in more depth. Some of our previous assumptions may not be correct. For instance, despite their body size and mobility, rock wallabies do not disperse as extensively as once thought (Potter et al 2012). For many of the NOK species, basic information on their populations and their movements could be gained using mark-recaptured studies along with undertaking genetic studies. Because of this lack of information in the NOK, the following research questions regarding the small mammal species should be posed:

- What is the life history of the species?
- What is the size of the populations and their densities?
- What is the species' roles and niche within the landscape?
- What are the movement patterns of the species?
- What is their survivorship and reproductive success?
- What is the size of their home range?
- What are their dispersal patterns both across the vast ranges and/or at a local scale through adjacent gorges?
- Is the landscape connectivity the same for all the small mammal species?
- Is there a relationship between morphology and dispersal for NOK small mammals?

- What is their rate of colonization and persistence (particularly in relation to fire and cattle)?

5.6.2 Conservation status and distribution

The current assessments of the status of the small mammal species may be inaccurate given the extensive data paucities in the region. It may be that some species are rarer than currently thought, and/or locally restricted and hence may warrant conservation status. Further research into the occurrence of small mammal species more broadly across the region should provide a better indication of not only their distribution but also contribute important conservation information at both local and region scales. Research questions to investigate this could include:

- Do current distribution projections accurately represent species' occurrence?
- What are the long-term drivers of change in species presence/absence in the NOK?
- Do species still occur at locations where they were previously detected?
- Where are the strongholds for rare and threatened species and what are the environmental conditions?

5.6.3 Rainforests and refuges

The rainforests of the NOK support a range of species and are characterized by a high level of endemism. There has not been a systematic survey of rainforests in the region since the 1990's. Future research should investigate the value, distribution and health of the rainforests across the NOK. This includes undertaking a broad-scale survey work to identify the locations of rainforest patches and systematically surveying the fauna inhabiting them. Consideration should be particularly given to those that form corridors and the value of protecting this network. Conversely, isolated rainforest patches should also be surveyed for species that may persist, before the habitat potentially becomes degraded. Other habitats, such as deeply dissected sandstone, mangroves and mound springs may also form important refuges for small mammal species. However, the occurrence and usage of these environments in the NOK is not well known. Research into the value and distribution of rainforests and other refuges should include:

- What is the current distribution of rainforests throughout the NOK?

- What is the condition of rainforests throughout the NOK?
- Has the condition of the rainforests changed and what may be the cause of any changes (ie cattle, fire)?
- How valuable are rainforests as refuges for the various small mammal species?
- What are the different types of refuges in the NOK? What are their characteristics? What do they provide?
- Which broad habitat types provide refuges for small mammal species?
- Which landsystems provide the most valuable refuges?
- Are there biodiversity ‘hotspots’?

5.6.4 Invasive species – cats and cane toads

Cats have now been shown to have a great impact on native fauna and presumed to occur throughout the NOK. However, their occurrence and density has not been investigated. Similarly, given cane toads have now invaded the NOK, it is timely to undertake investigations of their distribution and movement patterns throughout the NOK systems. Furthermore, their presence should be observed in conjunction with baseline monitoring data to help describe the impact they have had, and are having, on small mammal species (and other fauna). Extensive research should be undertaken in relation to the effect(s) of both cats and cane toads. At a minimum, basic investigations should include:

- What is their current distribution, density and their dispersal patterns?
- What is their predicted distribution over time?
- What impact are they having on NOK small mammals?
- Do changes in small mammal relative abundance occur following toad arrival and are these the same as those found elsewhere in northern Australia?
- Is cat abundance and behaviour and efficacy similar across different landscapes?

5.6.5 Cattle

The influence of cattle grazing in the NOK has not been broadly assessed. Cattle are free roaming through most of the region, with higher management on dedicated pastoral stations and control measures in some parts of the region. Nevertheless, the vast extent of the region, along with the monsoonal climate, means the maintenance of cattle exclusion fencing is exceptionally challenging. Grazing is widely accepted as having a major impact on the Australian landscape. Research into the impact of cattle should consider changes observed following cattle removal. The questions that should be investigated, amongst others, include:

- What is the influence of cattle on vegetation structure and composition?
- What effect does cattle removal have on species succession, community structure and relative abundance?
- Are observed changes of both small mammal species and community similar in different habitat types?
- Which habitats and species are most affected by cattle? Positively and/or deleteriously?

5.6.6 Fire

The mechanisms and drivers that influence small mammal relative abundance, recovery following fire and/or persistence are yet to be deciphered for the NOK, northern Australia or even globally (Griffiths and Brook 2014). Experiments with fire should include a range of exclusion zones to create different fire ages with ongoing monitoring. Investigations should consider populations and species' survival, recolonization and community changes with time since fire. A range of variables have been proposed, including fire frequency, intensity and time since fire, with the importance of these varying across different studies. Key research questions that should be posed regarding fire include:

- How does fire frequency affect the small mammal species and their community? Is this consistent across the different broad habitat types?
- How does fire intensity affect the small mammal distribution, abundance and community? Is this consistent in different broad habitats?
- How does fire extent affect the small mammal species and community? Is this consistent in different broad habitats?
- How does time since fire affect the small mammal species and community? What is the succession of species post-fire?
- How does the interaction of the key fire variables affect small mammal species?

5.6.7 Geographic Information Systems

The spatial imagery that is available for the NOK should continue to improve, and in the not too distant future should capture a resolution that more adequately describes environmental variation. Of particular need is the ability to describe fire and vegetation patterns. Subsequently, further research into the use of environmental spatial data to describe species occurrence, relative abundance and habitat information should be undertaken. Key research questions should include:

- Can imagery differentiate savanna vegetation sufficiently to describe habitat types (ie woodland, shrubland or grassland) and height classes?
- Does spatial imagery and information correlate with small mammal species distribution and abundance?
- Can spatial information be used to accurately predict species occurrence and relative abundance?

5.6.8 Long-term change and drivers

Whilst taking into account many of the research questions raised above, the changes and ecological implications of the findings should be considered over time using long-term data. The lack of monitoring is a major hindrance for understanding across many regions in Australia, and this is particularly the case with the sparsity of information in the NOK. Investigation using repeated site surveys should be used to, at least in part, undertake long-term research. Extensive research should be planned to obtain a long-term data set using repeated monitoring sites. Relevant hypotheses should be proposed to undertake appropriate experiments to investigate small mammal responses to:

- rare events (ie rainfall, extensive fire)
- long-term changes in different broad habitats and/or systems
- time-lagged effects
- cumulative effects of change, stressors and/or proponents
- ecological patterns changing with the changing climate
- biodiversity ‘hotspot’ longevity and status

5.7 Conclusion

The NOK is one of two bioregions in Australia considered to have an intact fauna (Burbidge *et al.* 2008), yet there are many deficiencies in the knowledge of the small terrestrial mammal community found to occur in the region. The present study has demonstrated the potential biodiversity value of privately leased land in the NOK. The variation in the occurrence, and the responses, of species to environmental variation in this study, in conjunction with the imminent threat of decline, highlight the need for greater understanding within the region and for consolidated management practices that effectively engender long-term conservation.

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Appendices

Tropical Short-tailed Mouse
Leggadina lakedownensis

Appendix 1.

Broad habitat types distinguished on Doongan Station

Pkl, King Leopold Sandstones; Pkc, Carson volcanics; Qa, Quaternary alluvium; Czs, Cainozoic sediments; Czv, Cainozoic volcanic derived soil; Tp, Undifferentiated laterite (Williams and Sofoulis 1967; Derrick 1969).

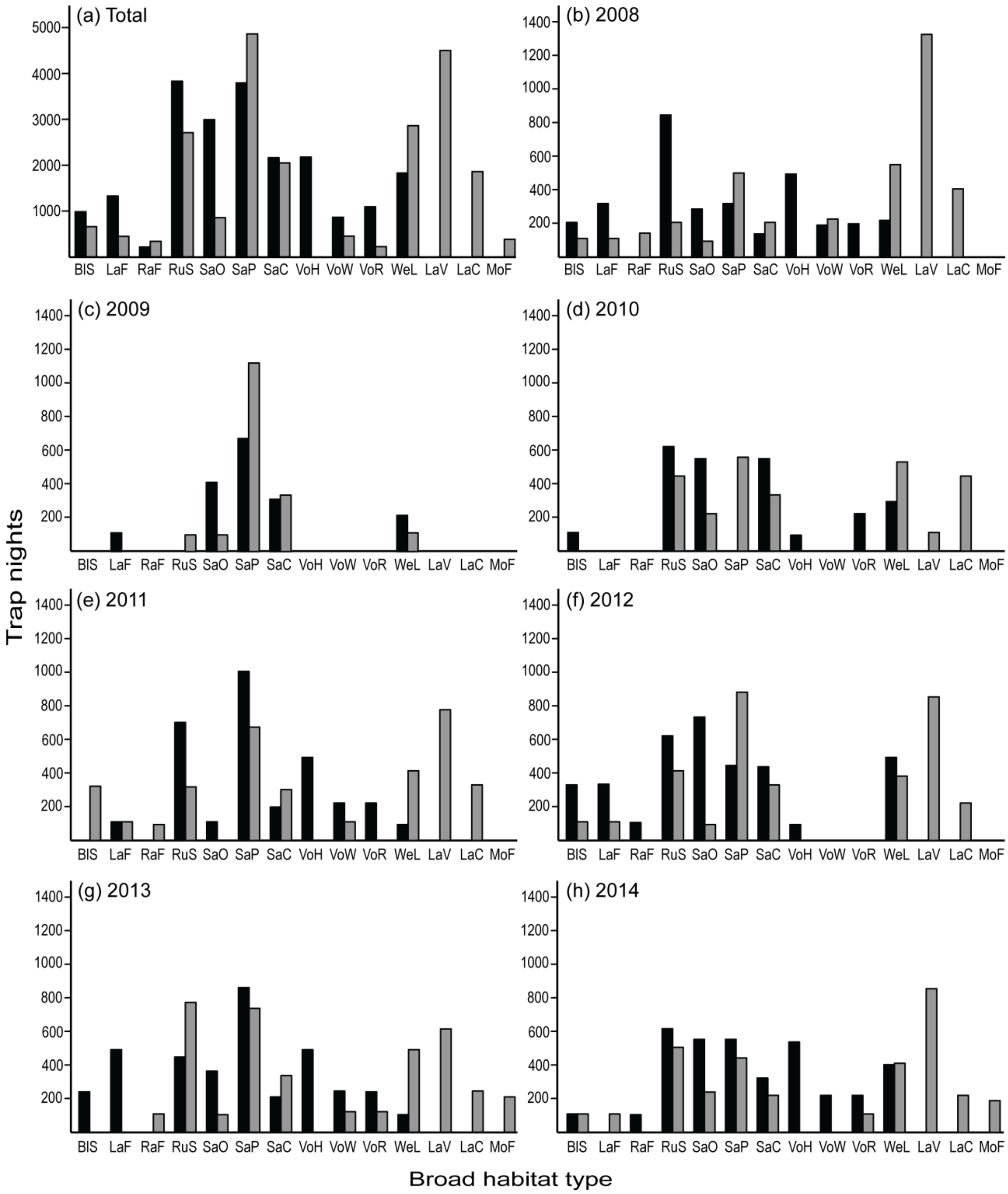
Landform	Description
Blacksoil (Czs, Czv)	Flat country with grey to black, deep, clay soils (including cracking clays). Scattered trees and occasionally woodlands of eucalypts (*Eucalyptus apodophylla*, *E. tectifica*, *E. tetrodonta*, *Corymbia latifolia*) and variably including thickets with *Antidesma ghaesimbilla*, *Terminalia* spp., *Bauhinia* sp. over native grasses.
Laterite flats (Czs)	Flats between volcanic hills and mesa with yellow to orange, clay to loam soils and often with lateritic gravel in the top soil. Eucalypt (*Eucalyptus miniata*, *E. tetrodonta*) woodlands with *Livistona eastonii* over mixed grasses (*Sorghum* spp., *Heteropogon contortus*).
Lateritic volcanic hills (Czs, Tp, Pkc, Qa)	Gently undulating country of low rocky hills and medium slopes on laterite-capped volcanic rocks with skeletal red earth and yellow or lateritic podzolics on lower slopes and depressions. Eucalypt (*Eucalyptus tetrodonta*, *Corymbia latifolia*) woodlands with variable midstorey species (*Terminalia canescens*, *Planchonia careya*, *Erythrophleum chlorostachys*) over mixed tussock grasses (*Eriachne avenacea*, *Chrysopogon* spp., *Themeda* spp., *Heteropogon* spp.).
Lateritic creekline (Tp, Qa)	Watercourses between volcanic hills and flats with deep brown to grey sand to clay–loam soils and occasional bare laterite. Narrow strip fringing watercourse of woodland of eucalypts (*Eucalyptus tectifica*, *Corymbia grandifolia*), *Melaleuca* spp. and *Pandanus* spp. over mixed native grasses.
Monsoon forest (Czs, Pkc)	Rocky sandstone boulder screes and gullies with shallow sandy soils in pockets. Low closed forest with occasional eucalypts (*Eucalyptus tectifica*, *Corymbia confertiflora*) over dense shrubs and small trees, with creepers and herbs.
Rainforest	Small isolated patches of variable soils in gullies, gorges and often damp swamps, sometimes along rivers or associated with seepage. Structurally diverse forest with a tall closed canopy and rainforest species including *Bauhinia* sp., *Mimusops elengi*, *Sesbania formosa*, *Terminalia* spp., climbers and ferns.
Rugged sandstone (Pkl)	Rugged sandstone crevice and boulder country with pockets of shallow soils. Structurally and floristically variable sandstone vegetation communities including eucalypt (*Eucalyptus miniata*, *E. tetrodonta*, *Corymbia latifolia*, *C. torta*) upperstoreys. Variable midstoreys often include *Terminalia* spp., *Acacia* spp., *Calytrix exstipulata*, *Erythrophleum chlorostachys* and *Buchanania oblongifolia*. Variable understoreys often including hummock grasses (*Triodia* spp.) and *Bossiaea bossiaeoides*.
Sandstone outcrop (Pkl, Czs)	Outcrop of rocks, boulders and often exposed bedrock with shallow/skeletal soils. Structurally and floristically variable vegetation communities as described in ‘Rugged Sandstone’.
Sandstone plains (Pkl, Czs)	Gently undulating sandstone plains and uplands with moderate to deep sand and loam soils, and bare rock sometimes present. Eucalypt (*Eucalyptus miniata*, *E. tetrodonta*, *Corymbia polycarpa*, *C. latifolia*) woodland communities and variable midstorey often including *Petalostigma pubescens*, *Pandanus spiralis*, *Planchonia careya* and *Erythrophleum chlorostachys*. Grassy understoreys including *Sorghum* spp. and *Chrysopogon* spp. and sometimes *Bossiaea bossiaeoides*.
Sandstone riparian formation (Pkl)	Watercourses between rugged sandstone and uplands with sandy alluvium and bare rock. Narrow strip fringing watercourse variably with eucalypts (*Eucalyptus tectifica*, *E. miniata*, *E. bigalerita*, *Corymbia grandifolia*, *C. bella*), melaleuca

Landform	Description
	species (*M. nervosa*, *M. argentea*) and pandanus (*P. spiralis*, *P. aquaticus*) over native grasses.
Volcanic hills (Pkc)	Volcanic hills and moderate slopes with basalt screes and red earths. Semideciduous vine thickets including *Bombax ceiba*, *Albizia lebbeck*, *Ficus* spp., *Terminalia* spp. along with *Smilax australis* and *Abrus precatorius* and other climbers.
Volcanic low woodland (Pkc, Czs)	Gently undulating country of low rocky hills and gentle slopes with igneous red earths and skeletal red earths, and heavy grey soils in shallow depressions. Eucalypt (*Eucalyptus tectifica*, *Corymbia grandifolia* alliances) woodlands with mixed tussock grasses (*Sorghum* spp., *Chrysopogon* spp., *Themeda australis*).
Volcanic riparian formation (Pkc)	Watercourses between volcanic hills with sandy alluvium and bare rock. Narrow strip fringing watercourse variably with eucalypts (*Eucalyptus tectifica*, *E. miniata*, *E. bigalerita*, *Corymbia grandifolia*, *C. bella*), *Melaleuca* spp. (*M. nervosa*, *M. argentea*) and *Pandanus Spp.* (*P. spiralis*, *P. aquaticus*) over native grasses (*Sorghum* spp.).
Wetland (Czs, Pkl, Pkc, Tp)	Ephemeral and permanent swamps, bog complexes and inundated flats with deep sandy loam to clay, grey to black soils. Scattered trees to open woodlands of eucalypts (*Eucalyptus bigalerita*, *E. latifolia*, *E. apodophylla*) and *Melaleuca* spp. (*M. viridiflora*), and occasionally *Banksia dentata*, over native grasses and sedges.

Appendix 2.

Comparison of trap nights in broad habitat types on Theda Station (black) and Doongan Station (dark grey) for total effort between 2008 and 2014 (a) and for each year 2008 to 2014 (b – h).

Habitats types: blacksoil (BlS), laterite flats (LaF), rainforest (RaF), rugged sandstone (RuS), sandstone outcrop (SaO), sandstone plains (SaP), sandstone riparian formation (SaC), volcanic hills (VoH), volcanic low woodland (VoW), volcanic riparian formation (VoR), wetland (WeL), laterite volcanic hills (LaV), lateritic creekline (LaC) and monsoon forest (MoF). Broad habitat types defined in Olds *et al.* (2016b [Chapter 2]).



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Pseudomys nanus

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