Determining the adequacy of Australia’s National Reserve System protected areas in protecting threatened mammal species

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Statement of Originality

I, Georgia Meredith, declare that this thesis is, to the best of my knowledge, original and solely my own, except where acknowledged and referenced, that the work presented in this document has not been submitted for any previous assessment*.

Signed: _______Georgia Meredith_______________

Due date: 28th October 2016

*Students undertaking ENVM4200 (Research Thesis) undertake GEOS6001, which is compulsory, and is intended to assist with the thesis development. For this reason some parts of the assessment for the two courses overlap.

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Abstract

Protected areas (PAs) are an important tool for conserving species threatened with extinction. The Convention on Biological Diversity (CBD) strategic plan (2020) has set formal targets for national PA estates via Aichi Target 11, which includes text on total area protected, effectiveness of management and connectedness of PAs. Australia, a signatory of the CBD, has met Aichi Target 11’s areal target of 17% under protection, yet there is considerable evidence that this has been inadequate to halt species declines.

While numerous studies have determined how well protected area estates cover threatened species distributions, none have considered species’ specific ecological requirements. This study determines whether 60 Australian threatened mammal species have adequate protection within the Australian PA estate when considering the minimum area required to support theoretical viable population targets. I achieved this by first assessing the actual coverage of the 60 species' distributions within the Australian PA estate using the latest data from the Species of Environmental Significance Database and the Collaborative Australian Protected Area Database. Using different published methods on minimum viable population and population density, I determined the minimum conservation area required to protect and support each of the 60 species.

I found that the Australian PA estate is not meeting its key objective of adequately protecting these 60 threatened species, with 49 having more PAs of an inadequate size than of an adequate size within their distribution. Seven species only have one PA within their distribution, leaving them highly vulnerable to catastrophic events such as bushfires. Of the species included in this study, 15% do not have any PAs of an adequate size to support an MVP threshold of 5000 individuals. A closer consideration of species’ ecological requirements is now urgently needed when considering further expansions of the Australian PA estate. Additionally, greater ecological knowledge e.g. updated population density estimates, is required in order to determine a more accurate minimum conservation area for some species, and in turn gain a better idea of the adequacy of their protection within the PA estate.

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Chapter 1: Introduction and Rationale

1.1 Introduction

Global species extinction rates are much now higher than historical levels, with human activities being the main driver of these losses (Pimm et al. 1995, Woodruff 2001, Ceballos & Ehrlich 2002, Ehrlich & Pringle 2008, Butchart et al. 2010). Today, more than 12,000 known animal species are listed in one of the three ‘threatened’ classes; Vulnerable, Endangered or Critically Endangered, on the International Union for Conservation’s (IUCN) Red List (IUCN 2016). This loss of biodiversity is leading to changes in ecosystems and their services that are essential to the survival of humans (Cardinale et al. 2012, Hooper et al. 2012, Hill et al. 2015).

Protected Areas (PAs) have an important role to play in threatened species conservation, primarily through *insitu* conservation (CBD 1992, Venter et al. 2014, Watson et al. 2014). PAs are a common strategy used to combat biodiversity loss (Rodriguez et al. 2013). Australia’s PA network, known as the National Reserve System (NRS), consists of over 10,000 terrestrial PAs, covering approximately 17.8% of the continent, and include Indigenous PAs, national parks and private conservation reserves among others (CAPAD 2014).

The Australian National Reserve System Cooperative Program (NRCS) was implemented in 1993 after the country ratified the Convention on Biological Diversity 1992 (Boer & Gruber 2010). In 2000, the updated National Reserve System (NRS) was implemented with the aim of increasing the size of the PA network in order to reverse species’ declines (Watson et al. 2009, Watson et al. 2011). Adequately representing species, ecosystems and bioregions within an appropriately managed national PA network is one of the fundamental aims of the NRS (NRMMC 2009).

There has been considerable growth in the Australian PA system in recent years, from 9,340 terrestrial PAs covering 984,871km² in 2008 to 10,339 covering 1,375,016km² in 2014, an increase of approximately 39% (NRMMC 2009, CAPAD 2014, Barr et al. 2016). There was a large expansion of the total area of the NRS after the implementation of the government’s ‘Caring for Our Country’ initiative in 2008-2013, which led to more large Indigenous Protected Areas being gazetted in primarily arid areas (Taylor et al. 2014). Much of this growth has been in Categories V and VI of the IUCN Categories for Protected Areas, which are primarily managed for recreation and sustainable use of resources (Boer & Gruber 2010, CAPAD 2014). Currently, approximately 51% of terrestrial PAs fall into the stricter, biodiversity-focused IUCN Categories of PAs I-IV, while 49%
fall under Categories V and VI. Despite this growth in areal coverage, studies have shown that some important bioregions and threatened species’ ranges are not effectively protected within PAs, leading to calls to target PA expansion towards threatened species conservation (Taylor et al. 2011, Watson et al. 2011, Watson et al. 2014).

1.2 Research Objectives

This study aims to determine if the characteristics of the current NRS adequately protect Australian threatened terrestrial mammal species. ‘Threatened species’ are defined in this study as those listed as Critically Endangered, Endangered or Vulnerable in Australia’s national environmental legislation, the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act). Approximately 13% of Australian terrestrial vertebrates are listed under one of these three threatened categories (Watson et al. 2011). Focusing on mammal species in studies such as this is important as in the last 200 years almost half of known global mammal extinctions have occurred in Australia (Johnson 2006). Additionally, compared to other taxonomic groups, a greater proportion of mammal species are listed under the EPBC Act 1999. These species are still under pressure from threats such as land clearing, livestock grazing, increasing urbanisation, invasive species and changing fire regimes, further increasing the importance of their study (Evans et al. 2011, Taylor et al. 2011, Watson et al. 2011, Tulloch et al. 2015).

The overarching goal of the NRS is to 'develop and effectively managed a comprehensive, adequate and representative national system of protected areas’ to ensure the persistence of terrestrial biodiversity in Australia (NRMMC 2009 pp. 10). As such, this study will focus only on the terrestrial and inland water ecosystems covered within the NRS. Marine PAs are managed separately from the NRS by the Commonwealth government and have been excluded from analyses (Department of Environment n.d.(a)).

Previous studies on the adequacy of PAs in Australia have focused on the areal coverage and degree of representation of threatened species in the NRS, particularly with fish species (Devitt et al. 2015), as well as mammals, birds and amphibians (Lemckert et al. 2009, Watson et al. 2011, Venter et al. 2014). This study aims to fill a gap in the knowledge by examining the specific ecological needs of threatened mammal species and whether the NRS supports these adequately to ensure long term persistence. Studies focused solely on the total coverage of PA networks may overestimate the ability of these areas to adequately protect threatened species. Instead, a closer comparison between
the ecological needs of species and the characteristics of the NRS is required to determine the adequacy of the NRS to conserve these species.

1.3 Research Questions

This research focused on two key questions:

Research Question 1: *What are the current characteristics of the Australian NRS in regards to threatened mammal species?* This question aims to clarify what the relevant characteristics of the NRS are in relation to conservation of threatened terrestrial mammals. This included determining the proportion of each species' distribution that is protected under the NRS as well as the number and size of PAs present across each species’ range.

Research Question 2: *What are the characteristics of the NRS when minimum conservation area is taken into consideration?* This research question aims to determine what the areal characteristics of the current NRS are when individual mammal species’ persistence was considered. Mammals species persistence was based on a minimum conservation area calculated for each species by using set minimum viable populations (e.g. Traill et al. 2010).

1.4 Structure Of Thesis

This thesis will firstly cover the context of the NRS and a literature review which includes the current gaps in knowledge in the PA literature, as well as a summary of current methods to determine PA adequacy for threatened species. This is followed by an explanation of data sources, a detailed methodology, the results of analysis, discussion of these results and finally conclusions, limitations and directions for future studies.
Chapter 2: Context and Literature Review

This chapter covers the international context of this research, as well as a specific literature review on how adequacy of PA management is calculated in relation to species conservation. The literature review will cover a number of themes relevant to this study, including a critical look at the Aichi Targets, a review of PA expansion and management literature and previous studies into the adequacy of the Australian NRS system. Finally, existing studies and methods of determining PA adequacy will be critiqued.

2.1 Context

2.1.1 International treaties

Protected areas have been around for at least 150 years (Watson et al. 2014). However, a significant change in focus for PAs occurred with the development of international environment treaties that aim to stop the decline in biodiversity, such as the Convention on Biological Diversity (CBD) (CBD 1992, Davey 1998, Eagles et al. 2002, Tittensor et al. 2014). This shift has seen the major role of PAs change from preserving areas of natural beauty to attempting to achieve specific biodiversity conservation outcomes (CBD 1992, Davey 1998, Eagles et al. 2002, Tittensor et al. 2014). Today, PAs are created to contribute to the livelihoods of communities, assist in the mitigation of climate change and improve economies through tourism, as well as conserve biodiversity and ecosystems (Watson et al. 2014).

The CBD called for the creation, funding and effective management of national PA networks in all signatory countries, and highlighted in situ conservation of species in PAs as an important way to maintain biodiversity (CBD 1992, Venter et al. 2014). The global PA estate has since expanded rapidly, from a few sites at the start of the twentieth century to over 160,000 statutory PAs that cover over 12% of the Earth’s surface (Watson et al. 2014, Polak et al. 2015). Unfortunately, support for PAs is decreasing globally, with reduced funding and ineffective management becoming more prevalent around the world (Watson et al. 2014). In addition to this, many countries still need to expand their national PA network to meet the basic coverage targets for the CBD (Watson et al. 2014).

After a failure to meet CBD commitments to reduce the loss of biodiversity by 2010, twenty ‘Aichi Targets’ were adopted at the Conference of the Parties in 2010 (Butchart et al. 2015). These are part
of the broader ‘Strategic Plan of Biodiversity 2011-2020’, which outlines new commitments to action this decade (CBD 2010a, CBD 2010b, Tittensor et al. 2014). The Aichi Target that is most relevant to this study is Target 11 (CBD 2010a).

Aichi Target 11 requires the governments of signatory states to commit to conserving more than 17% of terrestrial area and more than 10% of marine area (CBD 2010a, Butchart et al. 2015). Countries need to focus on ‘areas of particular importance for biodiversity’ through the creation of ‘ecologically representative’ PA networks (CBD 2010a, Butchart et al. 2015). Globally, only 14.6% of terrestrial areas and 2.8% of marine areas are under PA protection (Butchart et al. 2015). While there has been an increase in global terrestrial PA coverage area by 92% since 1990, this has generally been inadequately targeted and has led to shortfalls in many targets (Barnes 2015, Butchart et al. 2015, Watson et al. 2016). Other aspects of this Aichi target that are just as important for biodiversity outcomes include ensuring the effective management of PAs, forming PAs in areas that are ecologically representative and are of particular importance for both biodiversity and ecosystem services, and that these networks are well connected (CBD 2010a).

2.1.2 Australia’s response to CBD Aichi Target 11

Australia’s Fifth National Report to the CBD, the most recent report, states that it is ‘making significant progress towards Aichi Biodiversity Target 11’, with some ecosystems being well protected, while others are still under-represented in the NRS (Department of Environment 2014). This report also states that a key target for PAs in the Australian Biodiversity Conservation Strategy 2010-2030 has been met ‘well ahead of its timeline’. This target was to ‘achieve a national increase of 600,000km$^2$ of native habitat managed primarily for biodiversity conservation across terrestrial, aquatic and marine environments’ by 2015 (Department of Environment 2014).

Today, Australia has exceeded the percentage of terrestrial coverage of PAs of 17% set by Aichi Target 11; however, there is little talk about the other aspects of this Target, such as protecting ecologically representative areas that are well-connected and effectively managed (CBD 2010a, Department of Environment 2014, Taylor et al. 2014). While there are statements in this Fifth Report about this area and the rest of the NRS protecting habitat for threatened species, other studies have found that the NRS falls short of a fundamental aim to protect threatened species, with many species under-represented in the estate (Watson et al. 2011). Merely increasing the size of PA estates does not automatically conserve threatened species unless they are appropriately targeted to
areas that are a priority to the conservation of these species (Butchart et al. 2015, Watson et al. 2016).

Australia’s NRS has undergone rapid expansion over the past eight years (NRMMC 2009, CAPAD 2014) with much of this growth occurring in the less-strict IUCN Categories of V and VI (CAPAD 2014). Most of Australia’s PAs are small, however, with over 50% of PAs < 100 hectares in size, and 80% < 1000 hectares in size (CAPAD 2014). Due to these small sizes, there is uncertainty as to whether PAs present in a threatened species' range would be able to support a viable population of individuals. There are a number of other PA characteristics that are important to consider when deciding what could be improved in the NRS, including the size of PAs, connectivity and the hostility of the matrix between PAs. Due to time constraints on this research, I have focused only on PA sizes, and whether these match the ecological requirements of each species i.e. the minimum conservation area required to support a minimum viable population of individuals.

2.2 Literature Review

2.2.1. Criticism of Aichi Targets

The CBD’s Aichi Targets and their implementation have been criticised in the literature. Criticism of Aichi Target 11 tends to focus on the elements that have been largely overlooked by countries when forming PA networks (Tittensor et al. 2014, Hill et al. 2015). These elements include managing PAs for biodiversity needs, representation of a range of ecosystems and connectivity between PAs, as well as other effective area-based conservation measures (OECMs) that could be used in place of traditional PAs (Barnes 2015, Watson et al. 2016). As a result, many PAs are being formed in areas that do not conflict with human development, or areas with little value other than conservation, rather than in areas that are a priority for conservation (Hill et al. 2015). Critics also point out that focusing total coverage tends to overestimate what countries have achieved in the global PA network, and ignore the other goals of this target (Butchart et al. 2012, Tittensor et al. 2014, Butchart et al. 2015, Hill et al. 2015).

Other criticism of Aichi, and other, targets include whether they are appropriate for all countries and cultures or if they are even achievable over the set timeframes. Melick et al. (2012) suggest that, either in a cultural or technical sense, PAs are not always the ideal form of protection of natural areas for certain countries. In Papua New Guinea, resource extraction is central to development, and
most PAs have little government support and are ineffective (Melick et al. 2012). Perhaps different forms of PAs would be more effective in countries in this situation, or with different cultural circumstances. Attempting to achieve twenty separate targets could also be too ambitious for some countries who have limited resources to tackle biodiversity problems (Marques et al. 2014, Fenu et al. 2015). Fenu et al. (2015) uses the example of keystone-species rich areas such as Sardinia, an island in the Mediterranean Sea. This island is unlikely to achieve Aichi Target 12 (prevention of species’ extinctions) due to the limited amount of financial and human resources the island has to work towards this target (Fenu et al. 2015).

2.2.2 Global and Australian PA networks: expansion and management

Expansion

PAs are a widespread conservation tool used to protect habitat and biodiversity at a local, regional and global level (Chape et al. 2005, DeFries et al. 2005, Jenkins & Joppa 2009, Coad et al. 2013, Rodriguez et al. 2013, Rodriguez-Rodriguez et al. 2015). There is strong evidence that PAs are more effective at maintaining species population levels than other management methods (Taylor et al. 2011, Geldmann et al. 2013). They have an important role to play in threatened species conservation, primarily through in situ conservation (CBD 1992, Venter et al. 2014, Watson et al. 2014). Evaluations of the global PA network are important to determine what is required on a global scale, and then see if it is possible to complete these requirements at a finer scale within countries (Watson et al. 2014, Butchart et al. 2015). For example, it has long been said that biodiversity is declining globally and is continually under threat from habitat loss (e.g. (Pimm et al. 1995, Woodruff 2001, Butchart et al. 2010, Cardinale et al. 2012, Clark et al. 2013, Hill et al. 2015)). Following this, there have been calls to further expand the global PA network at a regional level, with the assumption that this will protect more species, ecosystems, and areas of important biodiversity at this level (Jenkins & Joppa 2009).

The global PA network has been expanding greatly in recent decades in response to pressures to increase its coverage (Watson et al. 2014, Polak et al. 2015). Despite this expansion, many bioregions are still inadequately protected (Jenkins & Joppa 2009). This is also true for Australia’s PA system (Spalding et al. 2008, Jenkins & Joppa 2009, Barr & Possingham 2013). Research suggests that further expansion needs to be more focused on areas of important biodiversity conservation value and be more targeted towards threatened species, rather than on merely...
increasing overall coverage to meet international targets (Rodriguez-Rodriguez et al. 2011, Butchart et al. 2012, Venter et al. 2014, Butchart et al. 2015).

There have been studies into the adequacy of Australia’s marine PAs in protecting threatened fish species e.g. (Bryars et al. 2012, Devitt et al. 2015), as well as some studies into the adequacy of PAs in protecting threatened terrestrial birds, amphibians and mammals (Lemckert et al. 2009, Watson et al. 2011, Venter et al. 2014). These previous studies focus on the overall coverage and representation of threatened species in the Australian NRS. These studies do not examine the ecological needs of Australian threatened mammal species and whether the NRS supports them in a way to ensure their long term persistence. The results from adequacy studies can shed light on how some PAs or PA estates, while meeting the coverage criteria, may not be effectively or adequately protecting threatened species.

Management

Beyond targets for PA coverage of a certain percentage of terrestrial and marine area (CBD 2010a), PAs must be effectively managed to ensure the achievement of basic objectives (Watson et al. 2014). More effective management has been shown to provide greater benefits to biodiversity than only expanding the PA network (Hockings et al. 2004, Coad et al. 2013, Coad et al. 2015, Costelloe et al. 2016). The growth in coverage of PA networks is simply not enough for the protection of species and ecosystems; studies into PA vegetation loss in South Asia shows that habitat conversion rates inside PAs can be the same as those of the unprotected lands surrounding them (Clark et al. 2013). Ineffective management can lead to invasive species encroaching into PAs, exploitation of species and overall environmental degradation, further decreasing a PA’s ability to protect threatened species (Watson et al. 2010).

The effectiveness of PAs also depends on the status and management of the land surrounding the PA (Schonewald-Cox et al. 1992, Wade & Theobald 2010, Laurance et al. 2012). A lack of proper management of the surrounding landscape can introduce new threats to biodiversity, thus impacting the integrity of a PA and limiting its effectiveness (Schonewald et al. 1992, Gaston et al. 2008, DeFries et al. 2010, Wade & Theobald 2010). Hence, bringing areas under formal PA agreements does not necessarily protect them from habitat or species loss within the PA (Craigie et al. 2010, Clark et al. 2013, Geldmann et al. 2013, Butchart et al. 2015, Sreekar et al. 2015a). Exploring the
hostility of the matrix and the connectivity between PAs is beyond the scope of this study, however they are important points to keep in mind when undertaking any study into PA coverage.

There are a limited number of national studies that explore how effective PAs are at protecting threatened species (Gaston et al. 2008, Tognelli et al. 2008, Wiersma & Nudds 2009). Some research suggests that past studies on the effectiveness of PAs rely on limited scientific evidence, or have exaggerated their effectiveness due to not separating the effects of the PA intervention from what would have naturally occurred in that region without formal protection (Rodriguez-Rodriguez et al. 2015, Sreekar et al. 2015a), e.g. (Bruner et al. 2001).

2.2.3 Existing methods to determine PA adequacy

*Population Viability Analyses*

Some authors argue that the issue of PA adequacy is best explored through Population Viability Analyses (PVAs) of the species being studied (Boyce 1992, Burgman et al. 1992, Possingham et al. 1993, Burgman et al. 2001). A PVA is a process that models the likelihood of a species’ population to persist for a set period of time using ecological data (Boyce 1992). MVPs are typically based on PVAs which use long-term population data to determine extinction probabilities (Akcakaya & Sjogren-Gulve 2000). Undertaking this method is not always possible, however, due to data and scope constraints of studies such as this one. Additionally, scientists and environmental managers cannot always wait for the collection of this data before making decisions (Lee & Jetz 2008). Another limitation of this method is that the MVPs calculated are context-specific, and are not typically able to be applied to other conspecific populations (Hilbers et al. 2016). The predictions of these models are also being questioned due to the models being based on a few types of data, and parameter estimates being based on little more than ‘educated guesses’ (Boyce 1992, Burgman et al. 1992, Possingham et al. 1993, Caughley 1994, Taylor 1995, McCarthy et al. 1996, Ludwig 1999, McCarthy et al. 2001). Traill et. al (2007) note that MVPs are an appropriate measure of a population’s viability in situations where is there insufficient data to complete a full PVA for a specific species (Shaffer et al. 2002). McCarthy et. al (2001) also make the point that no model can represent reality exactly, and so the predictions from PVAs will be imperfect. Ideally, real field data is used to determine the accuracy of these PVA models (McCarthy et al. 2001).

Burgman et. al (2001) developed an alternative conservation planning method to PVAs, which required a less extensive list of inputs into the system. This study, however, was completed for
vascular plants, which are not part of this study, and the method still requires more information, time and knowledge (they had experts decide on much of these information inputs) than is possible to know or acquire for this study. This method was geared more towards settings where a range of experts are available to help synthesise information to assist in policy decision making, and so it cannot be used in this study (Burgman et al. 2001).

**Gap Analyses**

Gap analyses are a method used to determine the adequacy of PAs in representing species (Santini et al. 2014). This method measures the percentage of a species’ range that is present in PAs and compares this to a set representation target; a minimum area that needs to be protected for that species (Scott et al. 1993, Jennings 2000, Rodrigues et al. 2004, Carwardine et al. 2009). These analyses have been widely applied to vertebrate species and in conservation planning methods to highlight potential new areas for conservation (Pressey & Margules 2000). The end goal is to determine if any species are not represented in the network at all (‘gap species’) or are not sufficiently represented (‘partial gap species’) (Gaston et al. 2004).

There are some drawbacks to this method, including the difference between population trends and representation, as well as representativeness of indicator species (Flather et al. 1997, Kujala et al. 2011). Despite these shortfalls, it is still widely used due to ‘its simplicity and wide applicability’ (Santini et al. 2014). Geographical ranges of species have been used in gap analyses, e.g. (Rodrigues et al. 2004, Tognelli et al. 2008), and so this method was used for my first Research Question. An assumption inherent in this method when using geographical distribution of a species is of uniform occurrence of that species within their range (Rondinini et al. 2006).

It must be noted that while species representation in PAs is required as a minimum condition of adequacy, it does not translate into ‘straightforward biological meaning’ (Rodrigues & Gaston 2001). It can be a bad proxy for species persistence as a species may have adequate overall coverage according to representation targets, however the PAs the species is present in may be too small to sustain a viable population (Santini et al. 2014). In this study, this will be balanced by my second research question, which calculates the minimum protected area required for long term species persistence and determines whether PAs within species’ distributions can support an MVP into the long term (See Section 3).
Minimum Viable Populations, Densities and Minimum Conservation Areas

A species population may be considered viable if it faces a relatively low risk of decline or extinction, or a low risk of its range being contracted within a set timeframe e.g. a few decades (Burgman et al. 2001). In this study, however, minimum viable populations (MVPs) will be defined as the smallest number of individuals that is required for a species’ population to persist in the environment, generally with at least a 90% certainty of persisting for at least 100 years (Shaffer 1981). Population size has been shown to be a determinant of wildlife population persistence (Reed et al. 2003, Sanderson 2006). Threats such as habitat modification and fragmentation, changed fire regimes and invasive species can impact on a landscape’s potential to sustain viable fauna populations (Schonewald-Cox & Buechner 1991). The concept of MVPs has been used widely in conservation management and species recovery programs, especially relating to small populations or populations restricted by range (Shaffer 1981, Lacava & Hughes 1984, Clark et al. 2002). MVPs are important as they can determine when a declining population becomes a small population (Caughley 1994), which are at a higher threat of extinction and stochastic environmental and demographic events (Melbourne & Hastings 2008).

MVPs were chosen over other methods of determining PA adequacy as the other methods, e.g. PVAs, were deemed unsuitable. Until recently, it was presumed that MVP estimates could only be created from detailed PVAs for each species. While carefully calculated, species-specific MVPs are ideal, management decisions cannot wait on the results of long-term studies required to obtain this data (Laurance 1991). A limitation of MVPs derived from PVAs is that there can be large differences between MVP estimates for the same species when using different survival probabilities and timescales (Traill et al. 2010). For example, MVPs have been found to vary by up to 10,000 individuals depending on whether the survival probability was set at >50% or >90% (Traill et al. 2010).

Through my research, I found very little species-specific MVP data for Australian threatened terrestrial mammals. Other methods for determining MVPs, such as the equation method by Wilson et al. (2010) and the Safe Index (Clements et al. 2011) seemed to hold more promise for determining MVPs of Australian threatened mammal species. Wilson et al (2010) estimated minimum conservation areas for 170 mammals in Indonesia using an equation adapted from the mean time to extinction equation by Lande (1993) (Figure 1). By using this new equation they were able to create equitable targets for all species by basing the target off two life history characteristics;
body weight and home range size (Wilson et al. 2010). The equation uses a variety of predetermined constants and the body weight data to get the carrying capacity of the population, which the authors then adjusted based on home range size of the species (Wilson et al. 2010).

\[ M = \frac{2K^b}{\sigma^2b^2} \quad K = \left( \frac{100000\sigma^2b^2}{2} \right)^{1/b}. \]

Figure 1: Lande (1993)’s original ‘Mean time to extinction’ equation on the left, and the modified version of this equation on the right used by Wilson et. al (2010). \( K \) = carrying capacity of the population, \( \sigma^2 \) = variance in the growth rate of the population, \( b \) = constant (calculated by \( \frac{[2r/\sigma^2] - 1}{} \)) and \( r \) = intrinsic mean growth rate of the population, \( M \) = mean time to extinction. In the second equation, 100,000 years is used as an approximate time to extinction for all species. Another study found that the maximum instantaneous rate of growth of a mammal population over a year (\( r_m \)) = 1.375W-0.315 \( (W \) = adult live body mass of females in kg) (Sinclair 1996). This study also found that the ‘instantaneous rate of change between censuses’ (\( r_t \)), also related to body mass, with \( r_t = 0.805V - 0.316 \) (Sinclair 1996). These two values are calculated to find \( b \), and then substituted into the equation to find \( K \) (Wilson et al. 2010).

There are a few issues with using this allometric method for determining minimum conservation area required for each species. First, some of the numbers used in working towards an answer could vary depending on how they are calculated. Second, these methods were derived theoretically, and have not been supported in empirical studies (Hilbers et al. 2016). MVP estimates calculated from this equation can be implausible, for example, an MVP of ~1 individual Asian Elephant (\( Elephas maximus \)) was calculated for a 95% survival probability over 100 years (Wilson et al. 2010, Hilbers et al. 2016). One method, however, that will be replicated in this study is that of extrapolating information from one species to similar species where certain ecological information is unavailable (See Section 3).

Instead of using this equation to calculate MVP estimates, set MVPs were used to calculate minimum conservation areas for each species. This method of using set MVPs has attracted controversy in the literature. The ‘SAFE Index’ (Species’ Ability to Forestall Extinction) was developed by Clements et al. (2011). It sets an MVP of 5000 individuals for all species regardless of taxa (Clements et al. 2011). This was first described in Traill et. al 2010, and is set in accordance with MVP estimates based on demographic and genetic information on different taxonomic groups (Brooks et al. 2006, Traill et al. 2007, Traill et al. 2010). The authors state this is a ‘heuristic’ method; one that is not optimal but is sufficient for the immediate goals of preventing species
extinctions, especially where specific MVP knowledge on species is unavailable (Clements et al. 2011).

There are clearly several limitations to this method, such as the lack of consideration for the environmental context of these populations (Clements et al. 2011). Stochastic disturbances such as disease, fire and invasive species can change the species’ risk of extinction, and habitat fragmentation and connectivity can also play a role in reducing or increasing this risk (Clements et al. 2011). Additionally, other variables such as the variance of a population’s growth rate, the connectedness of different populations, home range size and life history traits are either equally or more important when determining a population’s viability (Lande 1993, Caughley 1994, Akcakaya et al. 2011, Beissinger et al. 2011, McCarthy et al. 2011).

While setting this standardised MVP has drawn criticism from the literature (Akcakaya et al. 2011, Beissinger et al. 2011, Flather et al. 2011, McCarthy et al. 2011), it is a good method to ensure consistency across my results. Using an allometric equation as per Wilson et al. (2010) is beyond the scope and time restraints of this study, and has inherent issues within the equation (Hilbers et al. 2016). Most set MVPs in the literature for mammals sit between 2200 and 7000 individuals (Reed et al. 2003, Traill et al. 2007, Traill et al. 2010), while some sit at ~1300 individuals (Brooks et al. 2006). Some published MVP estimates are as low as 20 individuals (Saether et al. 1998), 400 individuals (Flather et al. 2011) while others are as high as 50,000 (Flather et al. 2011) and 100,000 (Reed 2005). Lower estimates, such as in Brooks et al. (2006), tend not to account for demographic stochasticity, genetic changes or fluctuation in age structures, while higher estimates tend to take these factors into account, e.g. Reed et al. (2003) (Traill et al. 2007). Perceived differences in these estimates, however, could be due to the different timescales, extinction probabilities and definitions of ‘populations’ being used by different authors (Reed et al. 2003).

There are issues with large, set MVPs. An estimate of ~7000 individuals was estimated for vertebrates by Reed et al. (2003); however the authors state in that paper that large, continuous areas of suitable habitat to support adults of these species do not exist all over the world. An alternative to this would be to increase connectivity between patches of suitable habitat. Another alternative is the methods outlined in Hilbers et al. (2016). This research was published after data analysis for this study was completed, but is worth mentioning here. They created an allometric method that uses growth rates and body mass to provide context-independent MVPs (different from Georgian Meredith Georgia Meredith 19
PVAs) that are still tailored to a species’ ecology and are applied at the population level (different from set MVPs such as the SAFE Index).

For this study, seven set MVPs were chosen based on published estimates; 100, 500, 1000, 3000, 5000, 7000 and 20,000 individuals. 100 and 20,000 were chosen to represent the extreme estimates of MVPs (Saether et al. 1998, Reed 2005), 5000 links to the SAFE Index and other recent and older published estimates (Thomas 1990, Frankham 1995, Clements et al. 2011), while 3000 and 7000 come from recently published estimates (Reed et al. 2003, Traill et al. 2007, Traill et al. 2010). While set MVPs may be controversial in the literature, conservation policy makers need targets that are relatively easy to use and apply to a range of species in order to take appropriate action as quickly as possible.
Chapter 3: Methods

3.1 Data Sources
The data for this study has been drawn from a number of sources. The maps and data on threatened species distributions were drawn from the Species of National Significance (SNES) Database 2013, as well as the Species Profile and Threats (SPRAT) Database 2015 (Department of Environment & Energy n.d.(b), (c)). The SPRAT database has been used to refine the SNES data to threatened species. The SNES database contains distribution information for all species of environmental significance, including invasive species such as feral cats and foxes. The SPRAT dataset also contains useful information on the species’ common name and its conservation status.

The Collaborative Australian Protected Area Database 2014 (CAPAD) contains maps and data on the current NRS and all the PAs present within it. The Australian PA estate follows the IUCN PA categories, in which Categories I to IV are managed primarily for biodiversity conservation, while Categories V and IV are managed primarily for recreation and sustainable use of resources. The PAs in the NRS ranged from less than one hectare in size to over 10 million hectares. CAPAD is published every two years by the Australian government, who collects this information from States and Territories around the country.

These databases combined provide the most up to date information on threatened species, their current distributions, and Australia’s PAs. Other data used for this study included population densities of each species from peer-reviewed literature and grey literature such as government Recovery Plans for some species. This was used to calculate the minimum conservation area required to adequately protect each species.

3.2 Methodology

3.3.1 Research Question 1 Methods

Research Question 1: What are the current characteristics of the Australian NRS in regards to threatened mammal species?

This question aims to clarify what the relevant current characteristics of the NRS are for this research. The objectives included determining the amount of NRS coverage that each threatened species has in its range, how many PAs are present in each range and finally the relationship
between the number of PAs present within each species’ range, and the size of those PAs. The results of this can be seen in the Section 4.

There are 77 terrestrial mammals in total listed in the SPRAT database. Of these, 44 are listed as Vulnerable, 28 as Endangered, four as Critically Endangered, and one is presumed extinct (See Appendix 2) (Watson 2016). Australian terrestrial mammal distributions vary greatly in size, from single site populations (e.g. Northern Hairy-Nose Wombat) to large distributions (e.g. the distribution of the Eastern Grey Kangaroo).

The SNES data on species’ distribution is made up of a number of data sources with varying levels of certainty. These include actual occurrences of the species (known distribution), known suitable habitat (likely to occur) and broader environmental envelopes (may occur). For this analysis, we excluded species with distributions categorised as ‘may occur’ (uncertain distribution estimates), following previous work (Watson et al. 2011, Barr et al. 2016). These species were excluded from analysis in both Research Question 1 and 2. A further eight species were removed from analysis due to issues with lack of ecological knowledge and data. For example, almost nothing is known about the population structure of the Northern and Southern Marsupial moles (*Notoryctes caurinus* and *Notoryctes typhlops*) (Benshemesh 2004, Bennison et al. 2014). These species were excluded from Research Question 2. The Bramble Cay Melomys (*Melomys rubicola*) is believed to have gone extinct in 2016 (Watson 2016), and so was removed from analysis. An additional eight species were excluded from analysis due to uncertain range estimates. The final count of species used in analysis is sixty eight for the first Research Question, and sixty for the second Research Question. A full list of species removed from analysis, and the reasons why, can be found in Appendix 1.

The next step was to determine the coverage of species’ distributions in the NRS. The total distribution of each species was taken from the SNES database. Representation targets were used to determine whether each species’ distribution has adequate coverage in the NRS, as per previous studies (Rodrigues et al. 2004, Watson et al. 2011, Polak et al. 2015). For species with a distribution of less than 10,000km$^2$, the targets were either 1000km$^2$ or 100% of its distribution included in the NRS, whichever was smaller. For species with a distribution of more than 10,000km$^2$, at least 10% of its distribution must be included in the NRS for it to be deemed under ‘adequate coverage’. The distribution data and gap analysis data are presented in Appendix 2, with a summary of results presented in Section 4 (Figures 2 & 3).
Next, the number of PAs within each species' range was determined. PAs were counted into seven categories; <10ha, 10-100ha, 100-1000ha etc up to the last ‘> 1,000,000’ category. The final counts of PAs are included in Appendix 2. The last step in this Research Question was to determine the relationship between the number of PAs in each species' distributions and the size of these PAs. This involved three sets of data; the distribution of each species, the number of PAs present in their range and the size of these. The final result is a graph that shows the relationship between the size and number of PAs in each species' range and the size of the species' distribution (Appendix 3).

3.3.2 Research Question 2 Methods

Research Question 2: What are the characteristics of the NRS when minimum conservation area is taken into consideration?

This research question aims to determine how the areal characteristics of the current NRS could be improved to increase mammal species’ persistence. MVPs were used to calculate the minimum conservation area required for species’ persistence, which was then used to determine whether the PAs present in the species’ range are of an adequate size to support viable populations of each species. Population densities were obtained to assist in the calculation of minimum conservation areas. Data on each species’ density was drawn from peer-reviewed literature, or from government Recovery Plan reports. This information was used to calculate the minimum conservation area required by species at different set MVPs.

When obtaining data for species’ population density, often multiple densities were found for the same species. When this was the case, the more optimistic (higher) density was used. That way, the results from this study will be optimistic in terms of minimum conservation area. The actual population density on the ground for the species may be worse, or different depending on suitability of habitat. For example, koalas are known to have different population densities depending on the area they are located (Phillips 2000, Stalenberg et al. 2014). The potentially optimistic nature of these densities must be taken into account when interpreting results for this research question.

Density data did not often go to the subspecies level, and so four species shared density data. i.e. data was found for Petrogale lateralis however there are four subspecies listed in the SPRAT database (Petrogale lateralis hacketti, Petrogale lateralis lateralis, Petrogale lateralis MacDonnell Ranges race and Petrogale lateralis West Kimberley race) so they all had the same density data for calculations of MVPs. Two species (Sminthopsis douglasi and Sminthopsis aitkeni) were allocated
density data from a similar species (*Sminthopsis psammophila*) listed on the SPRAT database, due to a lack of information on those specific species (Appendix 1). Seven species were allocated a density from a species not found on the SPRAT database (Appendix 1). This was due to the closest species to these in evolutionary terms not being listed as a threatened species, which means that these densities are particularly optimistic, and conclusions drawn from use of them must be interpreted with care.

Minimum conservation areas were calculated by dividing the MVP by the population density for each species to get a result in hectares. This resulted in seven results for minimum conservation area for each species, using MVPs of 100, 500, 1000, 3000, 5000, 7000 and 20,000 as discussed in Section 2.2.3. This is good information to have for future reference as some species require a higher MVP target (e.g. small mammals - see Hilbers et al. (2016)), and some larger species may require a smaller MVP (Flather et al. 2011). Only the result from the 5000 MVP was used for PA adequacy analysis and major discussion in this thesis (see Section 2.2.3). To determine PA adequacy, the list of PAs for each species was consulted and divided into ‘inadequate’ and ‘adequate’ sizes using the minimum conservation area calculated with the 5000 MVP.
Chapter 4: Results

This section presents the results of analysis for each Research Question. The first set of results on the current characteristics of the NRS include all species with higher confidence range estimates selected for initial analysis (see Section 3.3.1). The second set of results (minimum conservation calculations and PA adequacy analysis) excluded the eight species that did not have adequate ecological knowledge available to complete the analysis in the second research question. All data used for these analyses is included in Appendix 2.

4.1 Results for Research Question 1

4.1.2 Range Representation in the NRS

I found that 43 (63.2%) of the 68 Australian threatened terrestrial mammals included in this study have adequate representation under set targets (Figures 2 & 3). For species with a range of $<10,000\text{km}^2$, a total of 14 (37.8%) have adequate coverage of their range protected within the NRS under at least one of the targets, while 23 (62.2%) do not have adequate coverage under either of the targets (Figure 1). Two species met the 100% of range target, *Macropus robustus isabellinus* and *Lagorchestes conspicillatus conspicillatus*, however this is because their range is completely encompassed by one PA. For species with a range of $>10,000\text{km}^2$, 29 (93.5%) have adequate range representation in the NRS according to the target, while 2 (6.5%) have inadequate representation (Figure 2).

4.1.2 Number of PAs in species' range and relationship to distribution

Of the 68 species used for this part of analyses, 11 (16.2%) have only one PA present in its range (Appendix 2). Small to medium sized PAs (<0.5-1000ha) seem be present in species’ distributions more often than larger PAs (>1000ha) (Appendix 3). While some species have hundreds of small to medium PAs intersecting with their ranges, when larger PAs intersect with ranges they rarely number more than 10. Of the 12 species with the smallest ranges (between 1000-10,000ha), seven (58.3%) only have one PA present in their range.
Figure 2: Adequacy of species' distribution representation in the Nation Reserve System (NRS) (species with a distribution <10,000km²), based on range size and percentage of range included in the NRS. Criteria used are the representation targets from Watson et al (2011); for species with a range <10,000km², either 100% of its range or at least 1000km² must be protected for its representation in the NRS to be deemed ‘adequate’. Black line at the top of the graph shows the 100% target, while colours of the points show whether the species’ coverage is adequate or not based on the two targets (Green = 1000km² or more of the species’ range is protected under NRS or 100% of its range is included in the NRS, red = less than 100% of range and less than 1000km² protected under the NRS).

Figure 3: Adequacy of species’ distribution representation in the Nation Reserve System (NRS) (species with a distribution >10,000km²), based on range size and percentage of range included in the NRS. Criteria used are the representation targets from Watson et al 2011; for species with a range >10,000km², at least 10% of its range must be protected for its representation in the NRS to be deemed ‘adequate’. Black line on the graph shows the 10% target, while colours of the points show whether the species’ coverage is adequate or not based on this target (Green = 10% or more of the species’ range is included in the NRS, red = less than 10% of range is protected under the NRS).
4.2 Results for Research Question 2

4.2.1 PA adequacy using minimum conservation areas

This analysis found that 49 of the 60 threatened terrestrial mammal species used in this analysis have more inadequate than adequately sized PAs in their distribution (Figures 4 & 5). A total of 34 species have 10 or less adequately sized PAs in their distribution (Appendix 2). For species with less than 200 PAs in their range, nine species (15% of 60 species used for analysis); *Vombatus ursinus ursinus*, *Pseudantechinus mimulus*, *Potorous gilbertii*, *Leporillus conditor*, *Lasiorhinus krefftii*, *Lagorchestes hirsutus dorreae*, *Lagorchestes hirsutus bernieri*, *Isoodon obesulus nauticus*, and *Bettongia lesueur lesueur* have no PAs in their distributions that can be deemed adequate to support a MVP of 5000 individuals (Figure 4). Seven species (11.7%), *Conilurus penicillatus*, *Lagorchestes conspicillatus conspicillatus*, *Macropus robustus isabellinus*, *Notomys fuscus*, *Petrogale lateralis hacketti*, *Petrogale lateralis West Kimberley race*, and *Setonix brachyurus* have one PA in their range, which was deemed adequate to support a MVP of 5000 individuals (Figure 4).

Figure 5 presents these results for species that have over 200 PAs in their range. *Dasyurus maculatus maculatus* (southern latitude populations), has the highest number of inadequate PAs in any species’ range, 5128 (Figure 5). Due to the large scales involved in Figure 4, not all of adequate PA information can be seen clearly. *Dasyurus maculatus gracilis* has three PAs of an adequate size, *Dasyurus maculatus maculatus* (s. lat.) has 13, *Dasyurus maculatus maculatus* (TAS population) has 4, *Phascogale calura* has 12, *Sarcophilus harrisii* has 6, and *Sminthopsis aitkeni* has 3 adequately sized PAs (Figure 5). No species with more than 200 PAs in its range had zero PAs that were inadequate to support a MVP of 5000 individuals.
**Figure 4:** Number of PAs in each species' range that are of an adequate (green) and inadequate (red) size to support a minimum viable population of 5000 individuals. This graph represents species with less than 200 PAs in its range.

**Figure 5:** Number of PAs in each species' range that are of an adequate (green) and inadequate (red) size to support a minimum viable population of 5000 individuals. This graph represents species with more than 200 PAs in its range.
Chapter 5: Discussion

The Australian NRS is not meeting its key goal to support threatened species’ conservation, as it is failing to meet minimum conservation areas for many threatened terrestrial mammal species. Based on minimum conservation areas required to support an MVP of 5000 individuals, 49 of the 60 threatened terrestrial mammal species included in this analysis have more PAs of an inadequate size than of adequate size within their distribution. Of the 11 species that only have PAs of an adequate size within their range (i.e. no PAs of an inadequate size), seven species only have one PA present within their distribution, three have less than four, and one has 13 (Appendix 2). Of the 60 species included in this analysis, 15% do not have any PAs of an adequate size to support an MVP of 5000 individuals. The NRS is also failing to provide species with a high number of PAs of an adequate size to ensure species persistence, with 34 species having 10 or less PAs of an adequate size within its distribution e.g. *Conilurus penicillatus*, *Macropus robustus isabellinus* and *Setonix brachyurus*.

More species with larger (>10,000km²) distributions have adequate coverage in the NRS, compared to species with smaller distributions (<10,000km²). These species’ distributions may overlap more often with larger PAs, such as Indigenous Protected Areas (e.g. *Zyzomys maini* in Arnhem Land and *Dasycercus cristicauda* in inland Australia). Some species with smaller ranges (<10,000km²) are only present in a few areas which are under pressure from other threats such as logging (e.g. *Gymnobelideus leadbeateri*) or predation by invasive species (e.g. *Notomys fuscus*).

Previous research has shown that the NRS is broadly inadequate to protect threatened species (Watson et al. 2011, Polak et al. 2015). Here, with the incorporation of data on the minimum conservation area required to ensure species' long term persistence, I have shown that it is considerably less adequate than it previously reported. This is the first Australian study to focus on the ecological needs of threatened terrestrial mammal species and use these to determine whether they are adequately protected within the NRS. It addresses a limitation of the representation targets used in previous studies to determine PA adequacy (Rodrigues et al. 2004, Watson et al. 2011, Polak et al. 2015); that it can be a poor proxy for species’ long term persistence (Santini et al. 2014). This analysis has found that many of the PAs included in species’ distributions are inadequate to support MVPs of those species, despite 63.2% of species deemed adequately represented through the representation target analysis.
Results from Polak et al. (2015) cannot be compared with this study, despite only focusing on terrestrial species. There was no separation between different taxonomic groups, so results from mammal representation targets could not be compared. The results from Watson et al. (2011), however, largely agree with the results from the representation analysis completed in this study. I found that 63.2% (n=68) of threatened terrestrial mammals were found to have adequate representation within the NRS based on set targets, while Watson et al. (2011) found that 67.7% (n=55) of terrestrial mammals were protected at these same target levels. It is possible that, despite an increase in the coverage of the NRS between 2011 and 2016, species are worse off in terms of representation within the NRS. Studies from around the world have had similar results, where despite the increase in the coverage global PA estate, species declines are higher than ever (WWF 2008, Craigie et al. 2010, Barr et al. 2011).

These results come with some important caveats. Firstly, other important factors in determining PA adequacy, such as habitat suitability, could not be analysed given time constraints. This means that just because a PA was listed as present within a species’ range does not mean that the habitat in the PA is suitable for that species. For example, *Zyzomys maini* is endemic to the sandstone massif in western Arnhem land; however much of this area (over 34,000km$^2$) consists of habitat that is probably unsuitable for the species (Woinarski 2004). Future direction for studies could include habitat suitability analyses to determine whether the proportion of PAs that are included in a species’ distribution are of a suitable habitat to sustain an MVP of that species.

Second, commission errors (when a species is recorded as present in a PA when it is not) and omission errors (when a species is not recorded even though it is present) are a reality for these types of studies. Commission errors are more likely to occur in the SNES database, as there are other factors that determine whether a species is present in their distribution e.g. suitability of habitat (Rondinini et al. 2006). The result of these errors could be that I underestimated the number of species that have inadequate protection within the NRS (Watson et al. 2011). To determine the extend of this impact, intensive field work would be needed to ground-truth species occurrence within their distribution as presented in the SNES database; largely impractical for this study (Watson et al. 2011). Despite these impacts, they are not enough to invalidate the results, as the distribution maps for species are regarded as the best quality national data on species distributions.
Third, PAs were listed as part of a species’ distribution if they just intersected the species’ range and not completely covered it. I did not obtain the exact area of the portion of the PAs that are included in each species’ distribution. This meant that I could not calculate the proportion of a species’ protected range (amount of distribution present in the NRS) that was adequately or inadequately protected. Additionally, while some species only have one PA present in its distribution, this PA may be very large, and account for the majority of its distribution e.g. *Lagorchestes conspicillatus conspicillatus* has only one PA in its distribution however that PA measures over 25,000ha (Appendix 2). *Sarcophilus harrisii* has only 6 PAs in its range that meet the minimum conservation area to support 5000 individuals (Figure 4); however these are all over 95,000ha and hence would account for a good portion of the species’ overall protected distribution.

Setting general MVPs for a range of species continues to be controversial in the literature on the subject (See Section 2.2.3). In recent research, the authors found that an MVP of 5000 individuals would be mostly insufficient for mammals less than 1kg in body weight in poor habitat (Hilbers et al. 2016). It could be a high enough target in areas of good habitat quality and no other pressures that would cause declines, e.g. human development, invasive species (Hilbers et al. 2016). In the face of environmental stochasticity, however, Hilbers et al. (2016) suggests a higher MVP for mammals facing some pressures, up to a body weight of 50kg. In this case, these calculations of minimum conservation area for these species are likely to be optimistic, and in reality many species would need a larger area of suitable habitat to support a population that will be viable into the future. Even with this underestimation, the results look dire for species with no or few adequate PAs within their range, or only one adequate PA which is potentially vulnerable to threats and stochastic events.

Another limitation of this study is that all PAs were treated equally, regardless of what IUCN PA Category it has been assigned. Clearly, some categories are more suited to species conservation (i.e. Categories I-IV) while Categories V and VI allow some uses of the PA that may negatively affect threatened mammal species, such as grazing. As such, the adequacy of Australia's PA estate reported here is likely to be an overestimate.

While Australia has met and exceeded the Aichi Target 11 area coverage goal of 17% terrestrial area protected within the NRS, this study has shown that it is not enough to protect threatened terrestrial
mammal species. Species are not adequately protected across much of their range, due to PAs not meeting minimum conservation area targets. The current 17.88% of land that is contained within the NRS is not enough to conserve MVPs of these species into the long term. A recent study found that 24.4% of Australia’s terrestrial land would be need to be included in the NRS to achieve ecological and threatened species representation targets (Polak et al. 2016).

Focusing on the area coverage goals of the broader Aichi Target 11 has meant that other parts of the target such as effective management, connectivity, and ecological representativeness of the NRS have not been met. Effective management of PAs is an essential component to the success of the PA, and is one part of Aichi Target 11 that Australia has not met. Future gazettal of PAs in Australia needs to focus on ensuring that there are funds available to properly manage the PA for one of its key purposes; species’ conservation. Non-profits and non-governmental organisations such as Bush Heritage are taking on some of these management costs of new PAs through gathering donations from philanthropists and the wider community. While this is a step in the right direction, priority needs to be placed on the continued management of PAs after they have been gazetted. A PA is more than just its size and habitat type; if it does not have good management, threatened species within that PA may not persist into the long term due to impacts from various threats (See Section 2.2.2).

Connectivity between PAs is also essential to ensure species are able to adapt to threats such as the changing climate and increasingly more developed landscape (Hansen & DeFries 2007). Some species only have one PA present in their range, which makes them vulnerable to climate change, bushfires, disease or the incursion of invasive predators (e.g. cats, foxes) or invasive competitors that compete for food with the species (e.g. rabbits, introduced \textit{Rattus} species). Catastrophic events such as bushfires can seriously harm a threatened species’ chances of survival, especially when there are few populations of a species, such as when a bushfire wiped out half of the biggest population of \textit{Potorous gilbertii} in Two People’s Bay National Park in 2015 (Poloni 2015). Good connectivity between adequately sized PAs can reduce the impacts of these threats (Hansen & DeFries 2007). Threats are not affected by land tenure, for example, feral cats do not avoid an area because it is listed as a protected area. This means connectivity is important to facilitate the movement of species when a threat impacts a PA. The condition of the surrounding matrix of that PA, its level of use by people and different land uses and the level of suitable habitat all affect the
connectivity between PAs. While unable to cover this element of PA design in this thesis, it is critical to remember its importance moving forward.

Future directions for study include an increase in critical species data, habitat suitability analyses and an assessment of the connectivity of Australia’s PAs for different threatened species. To ensure appropriate conservation targets are set, uncertainty around species’ ecological requirements needs to be addressed. Mammals are some of the most highly conserved species in Australia and around the world, however some species could not be included in this analysis due to information such as population density being unknown. For other species, e.g. *Zyzomys maini*, density was derived from studies from one or two local sites, due to their not being any density information for its wider distribution (Woinarski 2004). Other species’ densities came from older studies, e.g. the latest density data found for *Bettongia lesueur lesueur* came from a study published in 1993. This is unlikely to reflect the species’ present density. Additionally, species’ may occur at different densities depending on the type of habitat, and where in the species’ range it is occurring. Better basic ecological knowledge of threatened species will allow more accurate and meaningful targets to be set in the future.

The NRS is not adequately protecting threatened terrestrial mammal species as 15% (9/60) of studied species do not have any adequate PAs within their distribution. While more work needs to be done to ensure accurate MVP and minimum conservation area targets, recent research suggests that these results are underestimating the adequacy of protection of these species. Expansion of the PA network is complicated and includes many biological, social and economic factors. It is critical, however, that specific ecological requirements of threatened species are used to inform expansion of the NRS to ensure the persistence of many threatened species into the future.
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Morris, K., P. Speldewinde and P. Orell "DJOONGARI (SHARK BAY MOUSE), Pseudomys fieldi, RECOVERY PLAN."


Appendices
Appendix 1: Species excluded from analysis and species with density data taken from other species

<table>
<thead>
<tr>
<th>Species name</th>
<th>Reason for exclusion from analysis</th>
<th>Excluded from analysis for Research Question 1/2</th>
</tr>
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<tbody>
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<td>Believed to have gone extinct</td>
<td>1 and 2</td>
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<tr>
<td><em>Chalinolobus dwyeri</em></td>
<td>Only lower confidence level range estimates</td>
<td>1 and 2</td>
</tr>
<tr>
<td><em>Hipposideros semoni</em></td>
<td>Only lower confidence level range estimates</td>
<td>1 and 2</td>
</tr>
<tr>
<td><em>Mesembriomys macrurus</em></td>
<td>Only lower confidence level range estimates</td>
<td>1 and 2</td>
</tr>
<tr>
<td><em>Notomys aquilo</em></td>
<td>Only lower confidence level range estimates</td>
<td>1 and 2</td>
</tr>
<tr>
<td><em>Potoros tridactylus tridactylus</em></td>
<td>Only lower confidence level range estimates</td>
<td>1 and 2</td>
</tr>
<tr>
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<td>1 and 2</td>
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<td>1 and 2</td>
</tr>
<tr>
<td><em>Zyzomys palatalis</em></td>
<td>Only lower confidence level range estimates</td>
<td>1 and 2</td>
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<tr>
<td><em>Miniopterus schreibersii bassanii</em></td>
<td>Lack of ecological knowledge on population structure</td>
<td>Only 2</td>
</tr>
<tr>
<td><em>Notoryctes caurinus</em></td>
<td>Lack of ecological knowledge on population structure</td>
<td>Only 2</td>
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<td><em>Notoryctes typhlops</em></td>
<td>Lack of ecological knowledge on population structure</td>
<td>Only 2</td>
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<td><em>Pipistrellus murrayi</em></td>
<td>Lack of ecological knowledge on population structure</td>
<td>Only 2</td>
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<td><em>Pteropus conspicillatus</em></td>
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<td>Only 2</td>
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<td>Lack of ecological knowledge on population structure</td>
<td>Only 2</td>
</tr>
<tr>
<td><em>Rhinolophus philippinensis (large form)</em></td>
<td>Lack of ecological knowledge on population structure</td>
<td>Only 2</td>
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<tr>
<td><em>Saccolaimus saccolaimus nudicliniatus</em></td>
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<td>Only 2</td>
</tr>
<tr>
<td>Species name</td>
<td>Density data used from this species</td>
<td>Details</td>
</tr>
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<td>--------------------------------------</td>
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<td><em>Phascogale calura</em></td>
<td><em>Phascogale tapoatafa</em></td>
<td>Evolutionarily the closest <em>Phascogale</em> species to <em>P. calura</em>. <em>Phascogale tapoatafa</em> not on SPRAT database</td>
</tr>
<tr>
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<td><em>Pseudantechinus mimulus</em></td>
<td><em>Pseudantechinus macdonnellensis</em></td>
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<td><em>Pseudomys australis</em></td>
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<tr>
<td><em>Pseudomys shortridgei</em></td>
<td><em>Pseudomys australis</em></td>
<td>Evolutionarily the closest <em>Pseudomys</em> species to <em>P. shortridgei</em>. <em>Pseudomys australis</em> not on SPRAT database</td>
</tr>
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<td><em>Zyzomys maini</em></td>
<td><em>Zyzomys argurus</em></td>
<td>Evolutionarily the closest <em>Zyzomys</em> species to <em>Z. maini</em>. <em>Zyzomys argurus</em> not on SPRAT database</td>
</tr>
<tr>
<td><em>Zyzomys pedunculatus</em></td>
<td><em>Zyzomys argurus</em></td>
<td>Evolutionarily the closest <em>Zyzomys</em> species to <em>Z. maini</em>. <em>Zyzomys argurus</em> not on SPRAT database</td>
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<tr>
<td><em>Sminthopsis aitkeni</em></td>
<td><em>Sminthopsis psammophila</em></td>
<td><em>Sminthopsis psammophila</em> is a SPRAT database species</td>
</tr>
<tr>
<td><em>Sminthopsis douglasi</em></td>
<td><em>Sminthopsis psammophila</em></td>
<td><em>Sminthopsis psammophila</em> is a SPRAT database species</td>
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<tr>
<td>Petrogale lateralis MacDonnell Ranges race</td>
<td>Petrogale lateralis</td>
<td>Petrogale lateralis (not subspecies) has density data available</td>
</tr>
<tr>
<td>-------------------------------------------</td>
<td>-------------------</td>
<td>---------------------------------------------------------------</td>
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<tr>
<td>Petrogale lateralis West Kimberley race</td>
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<td>Petrogale lateralis (not subspecies) has density data available</td>
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Appendix 3: Column graph showing the relationship between number of PAs in each species' range (circles) and their distribution (columns). Circle width represents number of PAs in that category, also shown by the numbers on top of each circle. Both axes are a logarithmic scale.