# SOUTHERN HAIRY-NOSED WOMBATS: WHEN, WHERE, HOW MANY, AND WHY

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# Preface

This thesis contains a combination of published manuscripts (chapters 2, 3, 4 and 7), manuscripts that have been submitted to a journal and are under review at the time of submission of this thesis (chapters 5 and 6), chapters that will be modified and submitted for publication at a later date (chapters 8 and 9), and chapters that are not intended for publication other than as part of this thesis (chapters 1 and 10).

To ensure consistency and for ease of readability, all manuscripts are presented in a similar format – i.e. published manuscripts have been reformatted from the format that was used by the relevant journals – although there may be some slight differences between them. In reformatting the published manuscript, some of the figures / images have been modified from the published versions by resizing or recolouring (some journals require black and white images).

# Table of Contents

# List of Figures

**Chapter 1**



**Chapter 2**

**Chapter 3**



**Chapter 4**



**Chapter 5**



**Chapter 6**

# List of Tables

# Abstract

In 2016 the conservation status of the southern hairy-nosed wombat was upgraded from ‘Least Concern’, to ‘Near Threatened’, based on an assessed population decline of up to 30% over the previous 25 years. Conversely, landholders in regions where wombats are present claim that the population has increased over recent decades. To resolve this discrepancy, we conducted a species-wide survey to determine overall wombat numbers and to establish any population trends. To do so, we had to develop reliable means of mapping the wombat distribution and estimating their abundance. We also conducted a literature review to estimate the likely distribution at the time of European settlement. We then used the findings from our survey to determine the factors which influence wombat distribution and abundance at different spatial scales.

At the time of European settlement the wombat distribution was split into two main groups separated by Spencer Gulf. The western population extended to Balladonia in Western Australia, while the eastern group covered Yorke Peninsula and the mid-north, Murraylands, and extended along the northern bank of the Murray River to Euston in New South Wales. The population experienced a dramatic decline in the late nineteenth / early twentieth centuries because of human persecution and competition from rabbits.

Using field surveys and the analysis of satellite imagery, we found that the wombat population has expanded in geographic range and overall numbers since the 1980s, although the rate of growth has not been uniform across the regions. Remote regions such as the Gawler Ranges and Nullarbor Plain have experienced the highest growth rates, while growth in the Murraylands has been moderate. We estimate the species-wide population at ~ 1.3 million. The population trend is difficult to establish, as earlier surveys did not include some areas in their assessments, including a population group in Western Australia that we surveyed for the first time. The index of 0.43 wombats / active warren, which we calculated by collecting video data on burrow occupancy rates, is similar to the indices that were calculated for the Murraylands in the 1980s / 90s.

The environmental factors which shape the wombat distribution are rainfall, rainfall variability, soil texture and vegetation. Wombats are absent from areas with a mean annual rainfall of <

154 mm, with abundance declining when rainfall is < 227 mm. Wombats are unable to construct warrens in areas where the soil clay content is outside the range of 10 - 40% – with a preferred range of 16 – 28%. Wombats also show a preference for open vegetation types, with a lower occupancy rate in closed vegetation types. While the overall distribution has fragmented and declined, abundance is probably higher in some areas due to the clearance of mallee woodlands.

The over-riding influence on whether wombats are present is land-use. While 38% of the wombat distribution is in protected areas and 50% on grazing land, wombats are virtually absent from croplands. This explains most of the fragmentary nature of the wombat distribution, and is the main cause of human / wombat conflict.

# Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution 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 the text. 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 and where applicable, any partner institution responsible for the joint-award of this degree.

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I acknowledge the support I have received for my research through the provision of an Australian Government Australian Postgraduate Award Scholarship.

Michael Swinbourne
26 November 2018

# Acknowledgements

This research was partially funded by the Australian Government through the Australian Research Council (ARC linkage grant # LP160100937).

When writing a thesis, it is traditional to thank everyone who has helped and supported you over the course of your studies. And while I will most definitely be doing that, I have decided to start my thanks and acknowledgements with an anecdote to put my research into perspective.

Not long after I started my research I was invited to attend, and present at, a Wombat Management Group meeting in Murray Bridge. Upon arrival I was shown into a conference room, and seated at the table were a number of people who I had never met before. As I shook hands and introduced myself, I was surprised to realise that I recognised the names of every single person in the room. These were the people who had written the papers that I had been reading on wombats – they were the people who had been researching wombats for many years and they were the experts on the subject. To be quite frank, I was a little star-struck. I highly respected their work and it was beyond my imagining that my work might one day be included in the canon of wombat research alongside theirs.

Several years on from that day and I now have a much closer working relationship with the people in this group. Sadly, some are no longer with us, but every one of them has provided me with assistance and with the inspiration to pursue my research. What has been surprising to me is that they now sometimes call upon me to ask my opinion or to talk about my work – even to ask me to work with them on projects. Isaac Newton is purported to have said, *'... If I have seen further it is by standing on the shoulders of giants…'*; and this is very apt in regard to my research. My work does not exist in isolation, but it is just the next step on a journey that started well before I came along. To that end I owe a great debt of gratitude to all the researchers who came before me, and I look forward to one day working with the ones who will come after.

It would not be a proper note of thanks without acknowledging the important roles of my supervisors, Associate Professor Bertram Ostendorf and Dr David Taggart. I have been lucky to have such knowledgeable supervisors to guide me in my research – Bertram for his knowledge of spatial sciences, and 'Tags' for his knowledge of wombats. But having supervisors who know the subject inside-and-out is one thing, but to me it is far more important to have a relationship with two men who I have enjoyed working with. Supervision of a mature-aged student like myself can be a tricky proposition, but Bertram and Tags have handled it with aplomb. Importantly to me, they have allowed me to pursue my own goals and to set my own workloads and standards without micro-managing, and for that I cannot thank them enough.

Along the way I have met a lot of other people who have assisted me to various degrees, and acknowledgement and thanks must go to all of them as well. Researching wombats involves a lot of time in the bush, and during my field research I have met many characters who have made the work both enjoyable and educational. To all the landholders where I conducted my research, who without exception were friendly, welcoming, and giving with their time, I extend a note of sincere thanks. And a special thank-you must go to Ron and Ingrid Dibbens, who have been the backbone of wombat research in the Murraylands for a very long time. I have spent many a night standing on the back of Ron's ute, driving around the countryside with a spotlight, GPS and notebook looking for wombats. And while most of the time I was 'freezing my arse off' and looking forward to getting into my warm (?) sleeping bag in the shearing shed, it was an extremely enjoyable experience and one which I would truly recommend to anyone.

Lastly, but by no means least – indeed, this is the person to whom I owe the greatest debt of gratitude – is my wife Alyce. When Alyce submitted her own PhD thesis earlier this year she suggested that I had played a major role by supporting and encouraging her. But while she might say those kind words about me, I don't think she truly appreciates what an inspiration she is to me and how much I have tried to emulate her achievements. Over the past few years she has supported me physically and emotionally during the periods of high workload, been my research partner - spending many fun days and nights in the bush together - and acted as a sounding board and helper when I became stuck for ideas or needed help with technology or data analysis. But far more than that, Alyce is the very reason why I chose to return to university to work towards an Honours and a PhD – to be like her. Alyce is far more than my partner, she is my inspiration. But most importantly of all, she has been, and always shall be, my friend.

# Chapter 1: A review of our current understanding of the distribution and abundance of southern hairy-nosed wombats (*Lasiorhinus latifrons*)


## Abstract

*Southern hairy-nosed wombats (Lasiorhinus latifrons) inhabit a fragmented distribution across the semi-arid regions of south-central South Australia and south-eastern Western Australia. Their burrowing nature can cause significant damage to agricultural property and infrastructure, and many farmers and graziers manage this issue by culling wombats and destroying their warrens. While permits for the destruction of wombats can be issued to landholders by the relevant government department, the amount and accuracy of the information on which management decisions are based is poor. Few surveys of wombat abundance and population trends have been undertaken, and much of the available data is out of date. These limitations are compounded by a poor understanding of the factors which affect wombat distribution and abundance, such as land-use, climate, competition, vegetation and soil type. Further research is needed to understand the true state of the population and the factors which influence the abundance of L. latifrons at different spatial and temporal scales.*


## Introduction

Since the European settlement of Australia in 1788, human influences have had a transformative effect on the landscape. Over the past 200 years, Australia has experienced one of the highest rates of animal extinction of any country in the world, with over 50 animal species - including 28 endemic land mammal species – being declared ‘Extinct’ (Woinarski *et al.* 2015). A further five mammal species are now designated as ‘Critically Endangered’, with 37 others being considered ‘Endangered’, and 67 ‘Vulnerable’ (Australian Government 2015). The main threat factors responsible for these extinctions and decline are predation by feral mesopredators, changed fire regimes, habitat loss, and competition from livestock and feral herbivores (Woinarski *et al.* 2015). Although the greatest decline and extinction rate has been experienced by smaller animal species (Chisholm and Taylor 2010), larger animals have also been affected. Anthropogenic factors have been the predominate reasons for variations in the population status of species as diverse as the salt-water crocodile (*Crocodylus porosus*)

(Fukuda *et al.* 2011), Australian sea lion (*Neophoca cinerea*) (Hamer *et al.* 2011), cassowary (*Casuarius* spp.) (Campbell *et al.* 2012), and koala (*Phascolarctos cinereus*) (Melzer *et al.* 2000).

Australia is home to three species of wombat (*Vombatidae*): *Vombatus ursinus* (common wombat), *Lasiorhinus krefftii* (northern hairy-nosed wombat) and *Lasiorhinus latifrons* (southern hairy-nosed wombat). Wombats are one of the largest burrowing animals on Earth, and can grow to over a metre in length and weigh up to 40 kg. While common wombats generally live in single burrows or small warrens with only a few burrow entrances (Evans 2008), hairy-nosed wombats often build communal warrens that contain multiple burrows (Steele and Temple-Smith 1998). At their largest, these warrens can contain up to 70 burrow entrances and cover up to a hectare, with large subterranean chambers and / or interlinking tunnels that allow the wombats to enter through one burrow entrance and exit through another (Swinbourne *et al.* 2016). These burrowing habits often bring wombats into conflict with landholders, and there is no doubt that the culling of wombats by farmers has been one of the major factors affecting their population status (Aitken 1971; Aitken 1973).

The conservation status of the three species of wombats varies, depending upon the source. The northern hairy-nosed wombat is listed as 'Critically Endangered' by both the International Union for the Conservation of Nature (IUCN) Red List and the Environmental Protection and Biodiversity Conservation Act 1999 (as amended) (EPBC). The common wombat is listed as 'Least Concern' by the IUCN, but 'Vulnerable' by the EPBC; while the southern hairy-nosed wombat is listed as 'Near Threatened' by the IUCN, but 'Least Concern' by the EPBC (Australian Government 2015; IUCN 2017). However, in the case of the southern hairy-nosed wombat, both the IUCN and EPBC cite a lack of detailed information to guide a definitive position on their conservation status.

In addition to this difference in conservation status, community views on whether the population of southern hairy-nosed wombats is currently contracting or expanding are based more on anecdote and personal opinion rather than on objective scientific analyses. On one hand, there are a number of community organisations that claim that wombats are endangered and that their numbers are declining (Stevens 2014). Alternatively, landholders throughout the agricultural regions of South Australia claim that wombats can now be found in locations and in greater numbers than at any time in living memory (Taggart *et al.* 2011). As a result, contradictory actions to both protect and control wombats are being undertaken simultaneously by different sectors of the community. As these actions are not being guided by robust scientific data, the implications for the species as a whole are uncertain. Consequently, most stakeholders agree that better information is required to guide management actions

This review will focus on the literature to determine our current understanding of the distribution and abundance of southern hairy-nosed wombats. Spatial and abundance variations that have occurred since the mid-twentieth century will be highlighted. Any gaps in the knowledge will be discussed, and opportunities for further research will be identified.

**Current and recent distribution**

Southern hairy-nosed wombats were first encountered by Europeans soon after the settlement of South Australia began in the 1830s (Allen 1839a; Allen 1839b). Their burrowing habits quickly brought them into conflict with the early settlers, who considered them to be pests and destroyed their warrens in order to build infrastructure and to open up the country for agriculture (Wood-Jones 1925). While southern hairy-nosed wombats were afforded some legislative protection against unfettered destruction from as early as 1919, it was not until 1964 that they were given protected status (Temby 1998). Even then they were still considered by many to be a pest, and the legislation which protected them also allowed for then to be culled to mitigate the damage that they caused to agriculture (South Australian Government 1972). Despite this, little was known about the status of the southern hairy-nosed wombat population, and there were no detailed attempts to map their distribution until the 1970s (Aitken 1971).

The latest published information suggests that the distribution of *L. latifrons* is currently restricted to six spatially fragmented sub-population groups and several translocated colonies. The largest groups are located in the Murraylands, Eyre Peninsula, Gawler Ranges (two), and the Nullarbor Plain from Penong in South Australia to the Western Australia border and beyond (St. John 1998). Scattered colonies can also be found on the Yorke Peninsula (Sparrow 2010), and small colonies have been reported near the confluence of the Darling and Murray Rivers in south-western New South Wales (Adam 1997) (Figure 1). Translocated colonies of approximately 300 animals are located on Wedge Island in the entrance to Spencer Gulf, and around 100 animals in Pooginook Conservation Park near Waikerie on the Murray River (Copley 1994; Ostendorf *et al.* 2016).

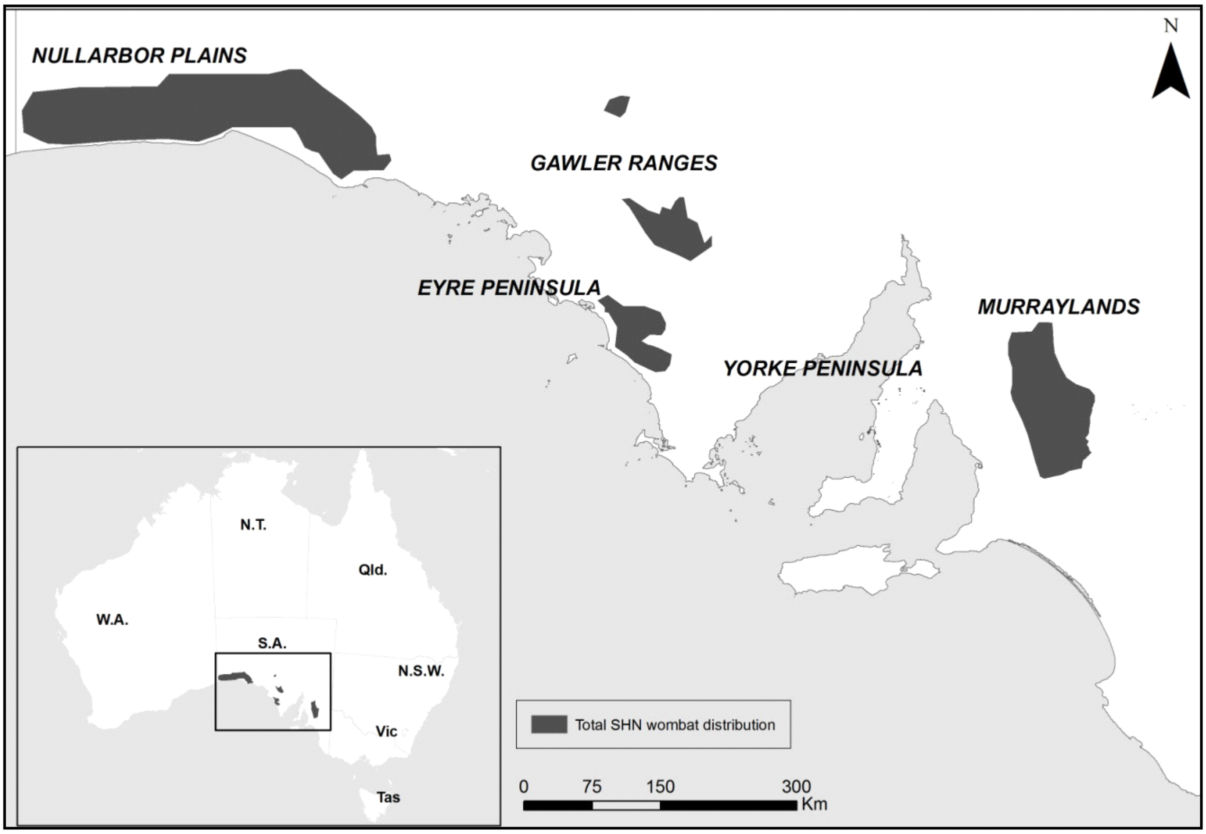


*Figure 1: Distribution of southern hairy-nosed wombats as at the most recent population surveys for each region (adapted from Taggart and Ostendorf 2012).*

While information on the distribution of *L. latifrons* prior to the 1970s is poor, the quality and timeliness of the information since that date varies considerably. Regions close to Adelaide, such as the Murraylands and Yorke Peninsula, have been the subject of several detailed studies, with the most recent in both regions being undertaken in the last ten years (Sparrow 2010; Taggart and Ostendorf 2012). Consequently, the quality of the information pertaining to those areas is probably quite good. More remote regions such as the Gawler Ranges, Western Australia, parts of the Nullarbor Plain and the Eyre Peninsula have had little to no attention, and the information on those regions is out-of-date and is unlikely to be accurate (Woinarski and Burbidge 2016).

*Murraylands*

The Murraylands region contains the closest southern hairy-nosed population to Adelaide, and for this reason it is the most studied. Information describing three broad-scale surveys is readily available - in 1981 (Tiver 1981), 1992 (McGregor and Wells 1998), and 2012 (Taggart and Ostendorf 2012). Numerous small-scale studies have also been undertaken at protected areas and research sites throughout the region, including Brookfield Conservation Park, Moorunde Wildlife Sanctuary, and at the University of Adelaide research facility (Kooloola) near Swan Reach (Taylor 1998; Taylor 2015).

The initial broad-scale survey was conducted in 1981 (Tiver 1981) using a combination of observations from a light aircraft and ground truthing. The survey found that the wombat population extended along the western banks of the Murray River from Morgan on the North West Bend (where the river turns south after travelling westwards for most of its length) to just south of Swan Reach. Isolated colonies were reported to occur as far south as Mannum, and in the north for up to 30 km to the north-west of Morgan. While the highest warren densities occurred on the calcarenite outwash plains close to the river, wombats could also be found westwards to the Sedan Hills, with colonies located along the banks of the ephemeral creeks in the foothills of the Mt Lofty Ranges (Figure 2). While there were no earlier surveys for comparative purposes, the report suggested that the 1981 distribution was probably less than it had been in the nineteenth century, but that it had been increasing since the 1950s.

A second broad-scale survey in 1992 (McGregor and Wells 1998) used a similar methodology to the 1981 survey, but substituted direct observations from an aircraft with airborne video recordings. A drought had occurred in the area in 1982/83 and the report suggested that the population was still recovering from its effects. The distribution had contracted along the borders and consolidated in the centre, with higher densities along the Murray River (Figure 2).

The most recent broad scale survey was conducted in 2012 (Taggart and Ostendorf 2012) using satellite imagery. This survey found that the population had returned to its 1981 extent and had increased its distribution to the north-west by approximately 30 km. There were also several fragmented groups stretching a further 30 km north along the foothills of the Mount Lofty Ranges, and a large population group on the northern side of Burra Creek (Figure 2). Unfortunately, whether these additional population groups had established since the earlier surveys cannot be determined, as neither the 1981 nor the 1992 surveys covered the areas to the north of the Morgan-Eudunda Road (Tiver 1981; McGregor and Wells 1998).

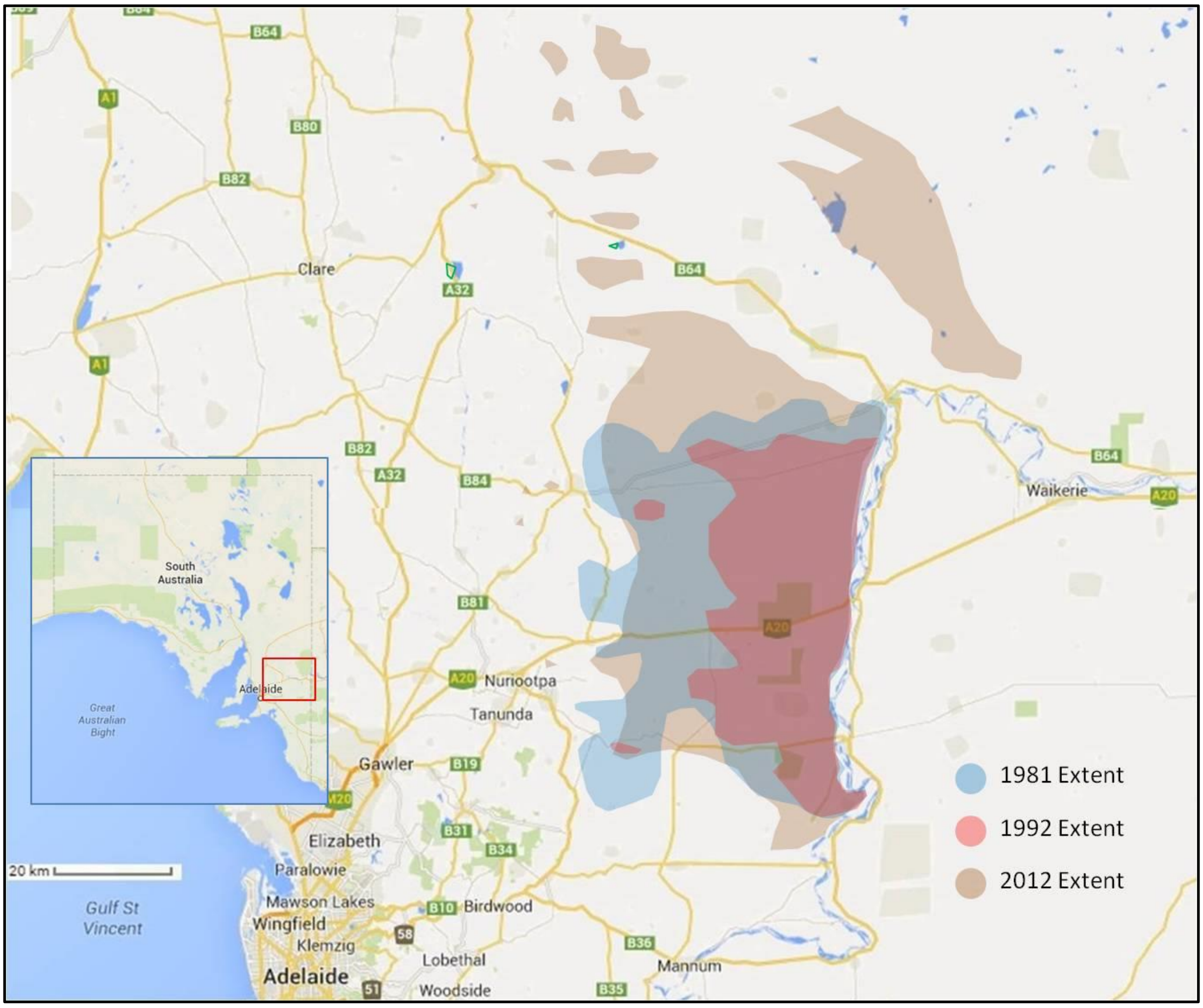


*Figure 2: Murraylands population group (adapted from Tiver (1981), MacGregor and Wells (1998) and Ostendorf and Taggart (2012)).*

Based on the evidence from these three surveys. the distribution of the wombat population in the Murraylands appears to have fluctuated over the past 30 years, with the extent larger in 2012 than it was in 1981. However, some caution should be exercised regarding this conclusion given that the earlier surveys did not fully cover the same area as the latter one. As the findings from the 1981 survey suggested that the distribution had increased since the 1950s, and the 2012 survey suggested that the population had increased since 1981, this would appear to indicate that the population has been undergoing a long-term increase in both distribution and abundance over the past 60 years. While the population surveys did not undertake research to determine the cause of this increase, the consensus is that it is related to the biological control of rabbits (Tiver 1981).

*Yorke Peninsula*

Surveys of the Yorke Peninsula wombat population have been conducted in 1971 (Aitken 1971), 1985/88 (St.John and Saunders 1989), 1994 (St. John 1998), and 2009 (Sparrow 2010). All of the surveys found that the population is highly fragmented with only a few geographically isolated colonies, most of which contain fewer than ten individual animals.

The number of colonies located by each of the surveys varied considerably. In 1971, eight colonies of various sizes were found. However, by 1988 only four of these colonies were still active. When the region was resurveyed in 1994, six colonies were located – one more of the colonies from 1971 (bringing the total to five of the original eight), plus one new colony. The disparity between these results was explained by the drought of 1982/83 which would have reduced the number of wombats in the area. Over the next few years wombat numbers recovered and they re-occupied areas that had been abandoned.

In the most recent survey conducted in 2009, thirty-four colonies were located, with the three largest having more than 150 animals each. Of the others, 22 were estimated to have less than ten animals and only five had more than 50 animals (Figure 3). The total number of wombats in the whole region was estimated at ~ 830 individuals.

While the difference between the number of colonies located in 1971 (eight) and 2009 (34) suggest that the distribution of wombats on Yorke Peninsula may have increased substantially in the intervening period, this is thought to be unlikely. A more likely explanation is that the earlier surveys did not locate all the extant colonies and these were not discovered until 2009 (Taggart and Sparrow pers. comm.). Given the fragmented and generally fragile nature of this sub-population, close monitoring is required to confirm the true nature of any variations.

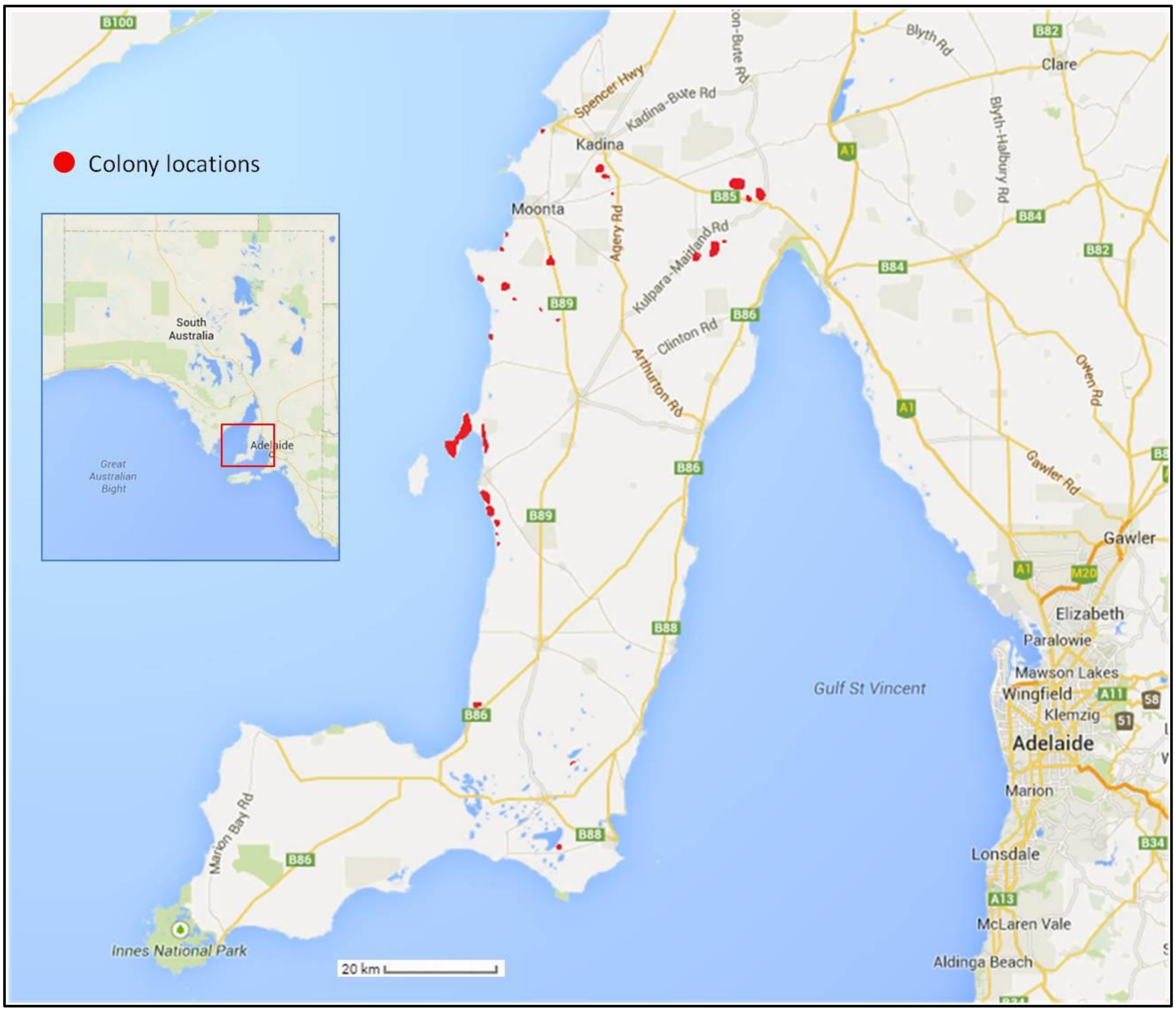


*Figure 3: Yorke Peninsula population group at the last survey in 2009 (adapted from Sparrow et al. 2010).*

*Eyre Peninsula*

There have been two broad-scale surveys of the Eyre Peninsula wombat population; in 1971 (Aitken 1971) and in 1989 (St. John 1998). Both surveys found that the main population group was located on the main area of grazing land on the peninsula; bounded by the Kulliparu, Cocata, Barwell and Bascombe Well Conservation Parks on the western side of the peninsula to the south of Venus Bay. The population had remained fairly stable within those broad geographic boundaries between the two studies (Figure 4). However, the status of colonies around the edges of the main group had fluctuated in response to seasonal variations in rainfall and vegetation growth (St.John and Saunders 1989).

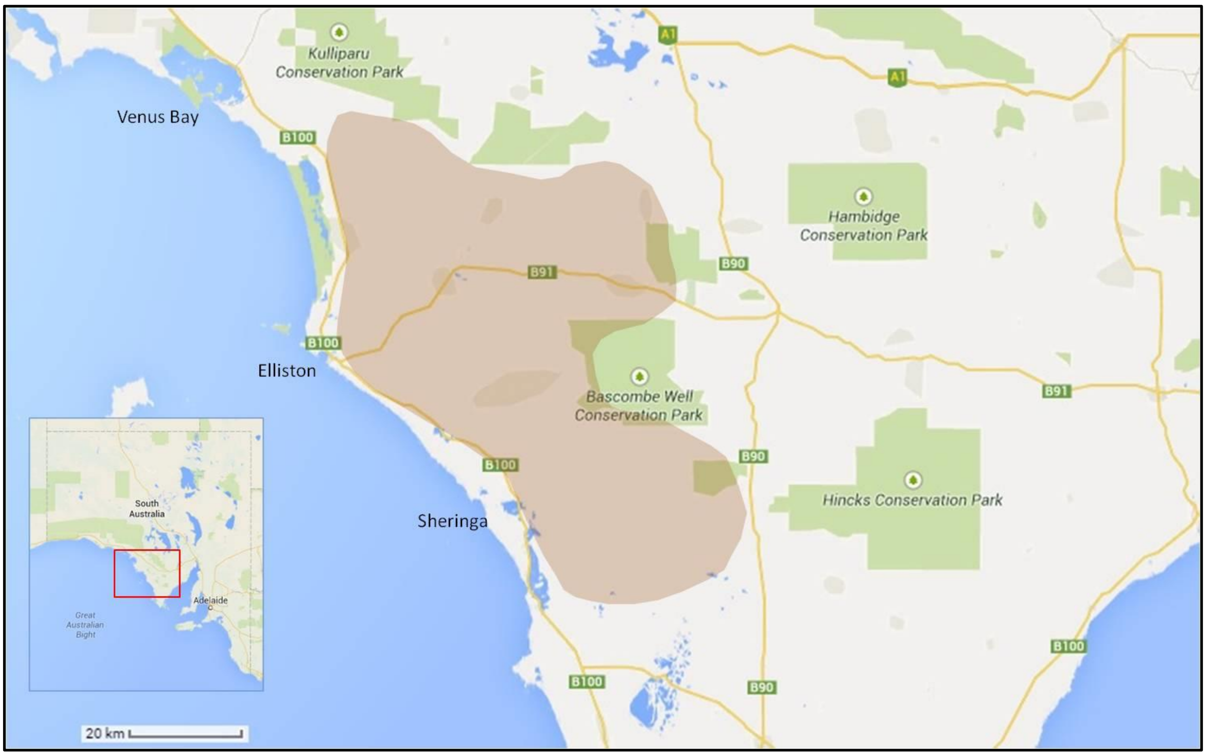


*Figure 4: Distribution of hairy-nosed wombats on the Eyre Peninsula at the last survey in 1989 (adapted from St John (1998)).*

While the Eyre Peninsula population appeared to be stable in the 1980s, there have been recent unconfirmed sightings of wombats further to the south and east, including in the vicinity of Port Lincoln and at locations along the east coast (Sparrow pers. comm.). Consequently, more up to date data is required to assess the details of any changes since 1989.

*Gawler Ranges / Lake Harris*

Two broad-scale surveys have been conducted of the wombat population in the Gawler Ranges / Lake Harris region; in 1971 (Aitken 1971) and 1985/88 (St.John and Saunders 1989). Both surveys located two sub-population groups; a group centred to the south and west of Lake Acraman and a smaller group on the western side of Lake Harris (Figure 5).


*Figure 5: Distribution of wombats in the Gawler Ranges and Lake Harris regions in 1988 (adapted from St John (1989)). Lake Acraman group (south) and Lake Harris group (north).*

**Lake Acraman.** The initial survey in 1971 suggested that the number of wombats in the region was low, with the main population group located close to the lake. Reports from graziers in the area at the time suggested that the distribution of wombats had increased by up to 30 km to the south and west since the early 1960s (Aitken 1971). A comparison between the 1971 data and surveys conducted in the 1980s showed that the distribution had continued to expand by a further 25 km towards the Gawler Ranges and had also spread to the north and east around the lake (St.John and Saunders 1989). This suggests that the wombat distribution in the area had been expanding markedly for at least the previous 25 - 30 years.

**Lake Harris.** Both the 1971 and 1988 surveys found a relatively small population of wombats in an area of ~ 500 $km^2$ in the catchment to the west of the lake. There appeared to have been little change in the geographic extent of the population between the two surveys. The sandy soils to the south and west of the area were thought to be unsuitable for burrow construction, and further expansion in these directions was thought to be unlikely (St. John 1998); although no comment was made on the potential for the population to expand northwards.

Since the most recent survey in 1988 there have been unconfirmed reports of wombats outside the last officially recorded distribution, including in the Gawler Ranges National Park to the south (Sparrow pers. comm.). Given the time that has elapsed since the last survey, more up to date information is required.

*Nullarbor Plain*

The Nullarbor Plains population is the largest and most geographically diverse group, with sections on either side of the dog fence and on agricultural land, crown land, protected areas and Aboriginal lands. It is also one of the most extensively surveyed, with broad area assessments being conducted in 1973 (Aitken 1973), 1980 (Tiver 1980), 1986 (St.John and Saunders 1989), and 2002 (Biggs *et al.* 2002).

A consistent theme across all surveys is that the distribution of wombats on the Nullarbor Plain has been expanding since the 1960s (Figure 6). In 1973 the western edge extended just to the west of the Western Australia border, with isolated colonies as far as Mundrabilla. At the same time the eastern edge was near Bookabie (Aitken 1973). By the mid-1980s the western edge had consolidated and the eastern edge had extended by 30km to near Penong (St. John 1998). The 1995 and 2002 surveys found that the eastwards expansion had continued by an additional 20 km past Penong, with an increase in population density in the recently inhabited areas (Biggs *et al.* 2002).

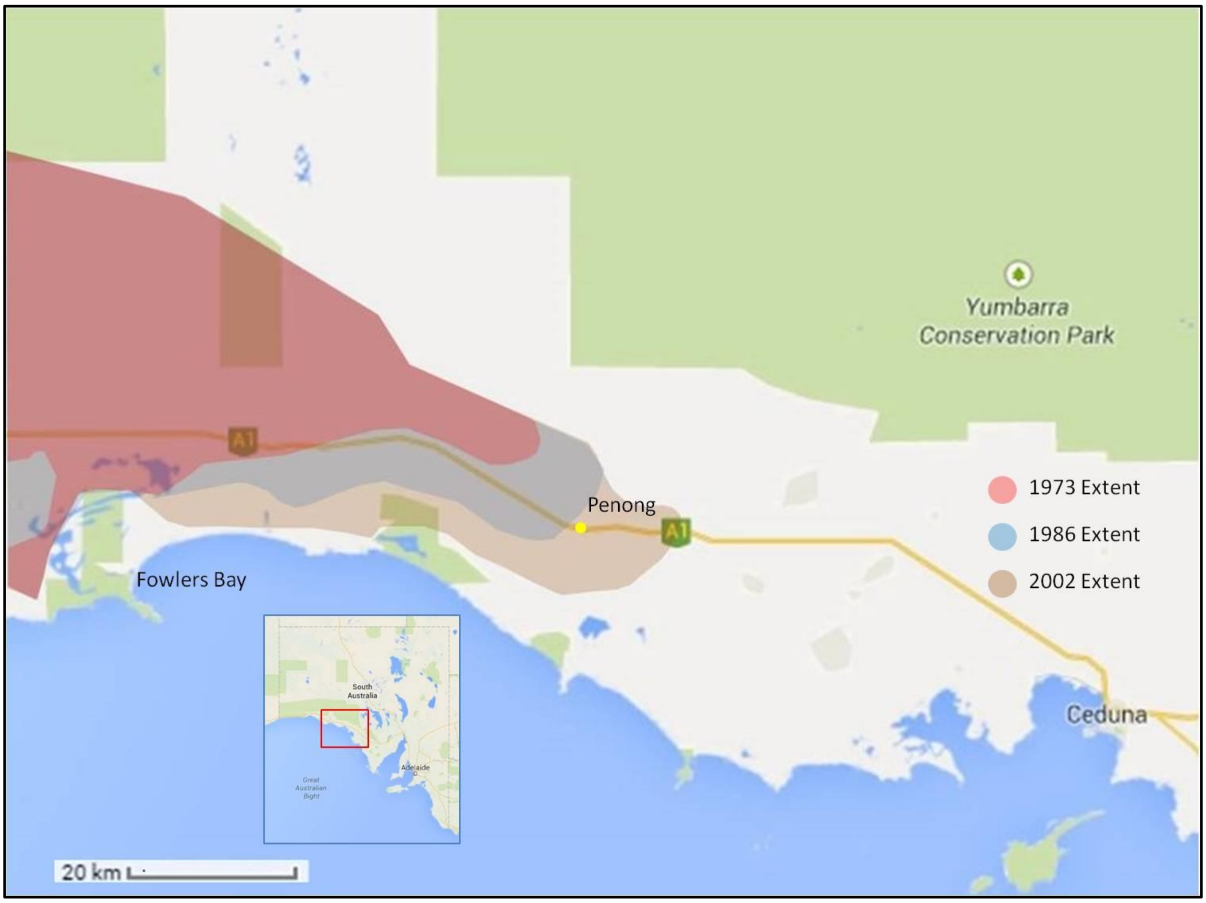


*Figure 6: Eastern end of the Nullarbor Plains wombat distribution showing the expansion from 1973 - 2002 (adapted from Tiver (1981), St John (1998), and Biggs et al. (2002)).*

*Western Australia*

While there have been isolated reports of southern hairy-nosed wombats occurring in Western Australia in locations such as Balladonia (Jenkins 1962) and Caiguna (Lowry 1967), there has never been a full scale survey to map their full distribution and to estimate their abundance. In his initial survey of the Nullarbor Plain from Ceduna to the Western Australia – South Australia border, Aitken (1973) reported on *"…outlying colonies… stretching to…. Mundrabilla, Western Australia, in the west. (Colonies have been reported from as far west as Caiguna, but I have not seen these)"*. However, Aitken's distribution maps did not extend over the border into Western Australia, and they also suggested that the main population group in South Australia did not extend any further west than around Koonaldo Cave (longitude 129.8 E), ~ 75 km to the east of the Western Australia border (Figure 7).

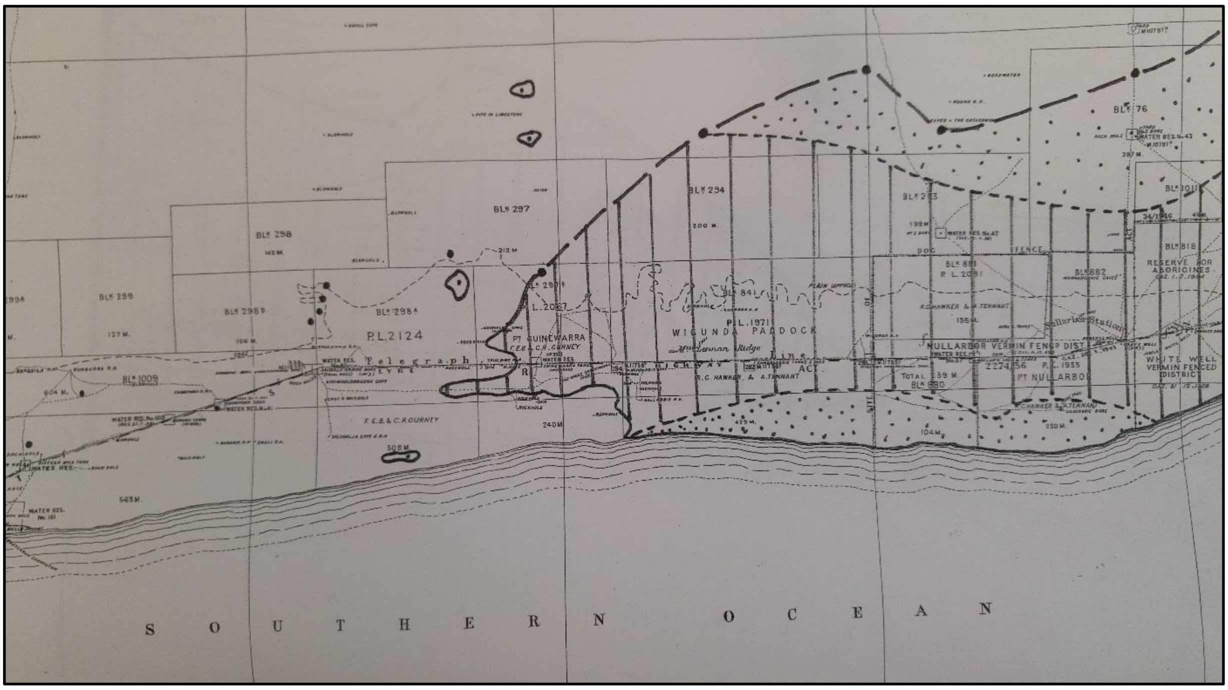


*Figure 7: The western edge of the distribution of southern hairy-nosed wombats according to Aitken (1973). The vertical lines shown on the map are 30 minutes of longitude (45 km at this latitude), and the left edge of the map is the Western Australia border.*

Aitken also reported that colonies to the west of the main population group appeared to be of recent origin, and that they may represent the first advances of a general population spread. While this is possible, the wide geographic spread of these colonies suggests that it is more likely they are remnant colonies which became isolated as a result of a population contraction sometime in the past. Mundrabilla is ~ 100 km across the border into Western Australia, with Caiguna being 250 km further (~ 350 km from the border). If wombats had only recently dispersed to these locations we would expect to find numerous colonies in the areas in between. In either case, it suggests that the distribution of wombats in Western Australia may either have once been extensive, or it is currently experiencing marked growth. Research should therefore be undertaken to resolve this and to determine the current population status of southern hairy-nosed wombats in the state.

*New South Wales*

There are no published surveys detailing the distribution or abundance of the southern hairy-nosed wombat population in New South Wales. The only information is contained in an endangered species listing from 1997, which suggests that two populations of between two and ten individuals each can be found between the Darling Anabranch and the South Australian border (Adam 1997) (Figure 8). The small size of the population and its geographic isolation from other population groups suggests that it is at high risk of local extinction from a range of threatening processes (Mace *et al.* 2008). Given the time that has elapsed since the listing (nearly twenty years), follow-on action to determine the current status of the population is strongly recommended.


*Figure 8: Location of the two southern hairy-nosed wombat colonies reported in NSW. In 1997 the colonies were reported to contain from between 2 - 10 individuals each, but there have been no follow-on reports since then regarding their status.*

### Overall distribution

The fragmented nature of the southern hairy-nosed wombat distribution begs the questions: when and why did it become fragmented? Was the distribution contiguous in the recent past and became fragmented as a result of anthropogenic factors, or did the sub-population groups become separated at an earlier time as a result of climate or other natural influences? How far did the distribution extend?

There are a number of maps available which purport to show that the likely pre-European distribution of all three species of wombats, with the distribution of southern hairy-nosed wombats being shown as contiguous from south-eastern Western Australia to the NSW border (Horsup 2012) (Figure 9). Given that the earliest surveys of the southern hairy-nosed wombat population did not occur until the 1970s (Aitken 1971; Aitken 1973), and there are reports of colonies of southern hairy-nosed wombats in NSW which are outside the mapped distribution, the veracity of these maps cannot be relied upon. There are also a number of fossil records from outside both the current and purported distribution of southern hairy-nosed wombats which provide evidence that the distribution was more widespread in the past, including from Kangaroo Island (Forbes *et al.* 2010), Naracoorte Caves (Reed and Bourne 2000), Lake Mungo (Hope 1978), and Lake Eyre (Webb 2009).

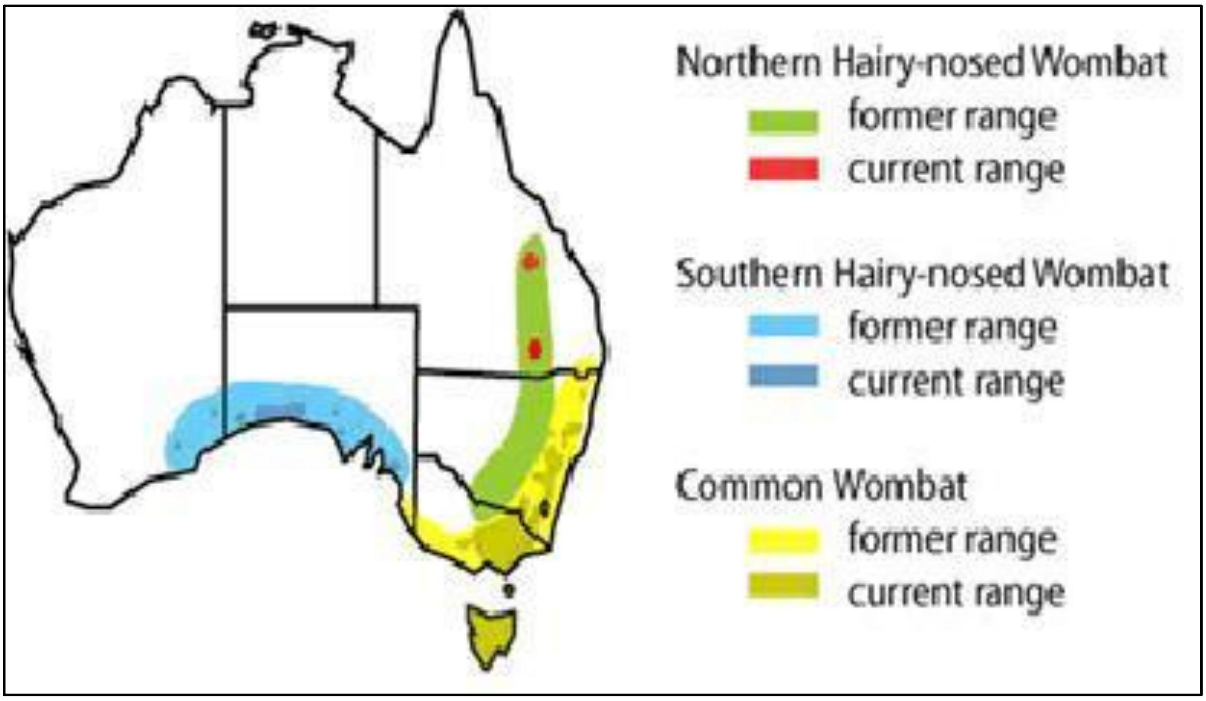


*Figure 9: Purported distribution of all three species of wombats prior to the European settlement (Horsup 2012). However, there are extant colonies of southern hairy-nosed wombats outside the distribution shown, which suggests these maps are unlikely to be accurate.*

Analysis of the genetic structure of the extant sub-population groups suggests that the wombats in the groups on each side of Spencer Gulf (Yorke Peninsula and Murraylands to the east; Nullarbor, Gawler Ranges and Eyre Peninsula to the west) appear to be more closely related to each other than they are to wombats on opposite sides of the gulf (i.e. between the Eyre and

Yorke Peninsula populations) (Alpers *et al.* 1998). This could suggest that the fragmentation of the wombat distribution on each side of Spencer Gulf occurred more recently than the separation of the Eyre and Yorke Peninsula populations. This, together with the evidence from the fossil record, suggests that there may be both paleontological and anthropogenic reasons for the current fragmentation of the wombat distribution. For example, the presence of southern hairy-nosed wombats on Kangaroo Island as recently as 11,000 YBP (Forbes *et al.* 2010) when the island was part of the mainland suggests that sea level rise following the last glacial maximum (LGM) (Lambeck and Nakada 1990) may have played a role in isolating the population on Kangaroo Island, which has subsequently died out.

If this is the case, given that past climate change would have played a significant role in determining the current wombat distribution, the potential for future anthropogenic climate change to cause further changes must also be considered. Further research should be therefore be undertaken to determine both the likely natural distribution of southern-hairy nosed wombats free of recent anthropogenic influences (fundamental niche), as well as the reasons for the fragmentation in the current distribution (realised niche), in order to better understand the potential impacts of future climate change (Pearson and Dawson 2003)

**Methodology to estimate abundance**

Although the first assessments of the distribution of southern hairy-nosed wombats were conducted in the 1970s, no attempts were made to estimate the population size until the 1980s. Because wombats are nocturnal and fossorial, estimating their numbers presents a number of challenges, and the surveys to date have relied on indirect indices rather than on counts of animals. The methodology used for all these broad scale surveys has been similar and is based upon the work initially conducted by Tiver (1980):

- Warrens are counted and the total is translated into a total number of active burrows – burrows which are currently being used by wombats - based on the number of warrens of different size classes.
- An index of ‘wombats per active burrow’ is then used to determine the final population estimate.

*Counting warrens / burrows*

The methodology used to count warrens has changed over time in response to advances in technology. The initial surveys estimated the distribution and density of warrens by an observer counting them from an aircraft (Tiver 1980; Tiver 1981). During the 1990s, airborne tape recordings were made which were later replayed and the warrens counted from freeze frames (Biggs et al. 2002). The most recent survey used Quickbird (< 1 m resolution) and Spot (2.5 – 5 m resolution) satellite imagery from Google Earth (Taggart and Ostendorf 2012).

To validate the airborne data, ground truthing surveys were conducted. These surveys indicated that both observer counts and airborne tape recordings are poor at detecting small targets, with up to one third of small warrens (< 5 m in diameter) and ten percent of medium warrens (5 – 15 m) being missed (Tiver 1981; Biggs *et al.* 2002). As a result, a correction factor was applied to the raw data based on a comparison between the ground and aerial counts.

Although the detectability of small warrens has been largely overcome by very-high resolution satellite imagery, some caution should also be applied to this methodology. Some areas are not covered by imagery at the same high resolution, warrens may be obscured by vegetation, and warrens which contrast poorly with their surroundings are difficult to detect. Ground truthing surveys are still required, even when using the best satellite imagery available (Taggart and Ostendorf 2012).

*Index of wombats per active burrow*

The index of wombats per active burrow has been calculated in several different locations using three different methodologies. The initial estimate was determined by the mark / recapture method (Sinclair et al. 2006) used by Tiver in his surveys of the Far West Coast (Tiver 1980) and Murraylands regions (Tiver 1981). Traps were placed at active burrow entrances in eight warrens of different sizes. Wombats caught in the trap were marked and released, and trapping was discontinued when the last marked animal was trapped on three consecutive occasions. Using this method, a ratio of 0.60 wombats per active burrow was determined for the Far West Coast population, and 0.43 for the Murraylands population.

Interestingly, although Tiver's initial estimate of 0.43 from the 1980 study is still in common use, an examination of the calculations in the study reveal several errors. Table 1 of Tiver's report shows the details of the wombats trapped and the number of active burrows in the surveyed warrens. Thirty wombats were trapped (16 males, 14 females) from 48 active burrows, which translates to a figure of 0.63 wombats / active burrow, not 0.43.

The second methodology used to estimate the number of wombats / active burrow was undertaken by Taylor (1998) in a long-term study at the Moorunde Wildlife Reserve; also in the Murraylands. Flap operated switches were placed at burrow entrances to record animals entering and leaving. The long-term trend in the number of active burrows did show a good correlation with the known population size, with the calculated ratio of 0.43 wombats / active burrow being identical to that calculated by Tiver (1980). However, the study also showed that this ratio could vary significantly, with no clearly discernible pattern (Figure 10).

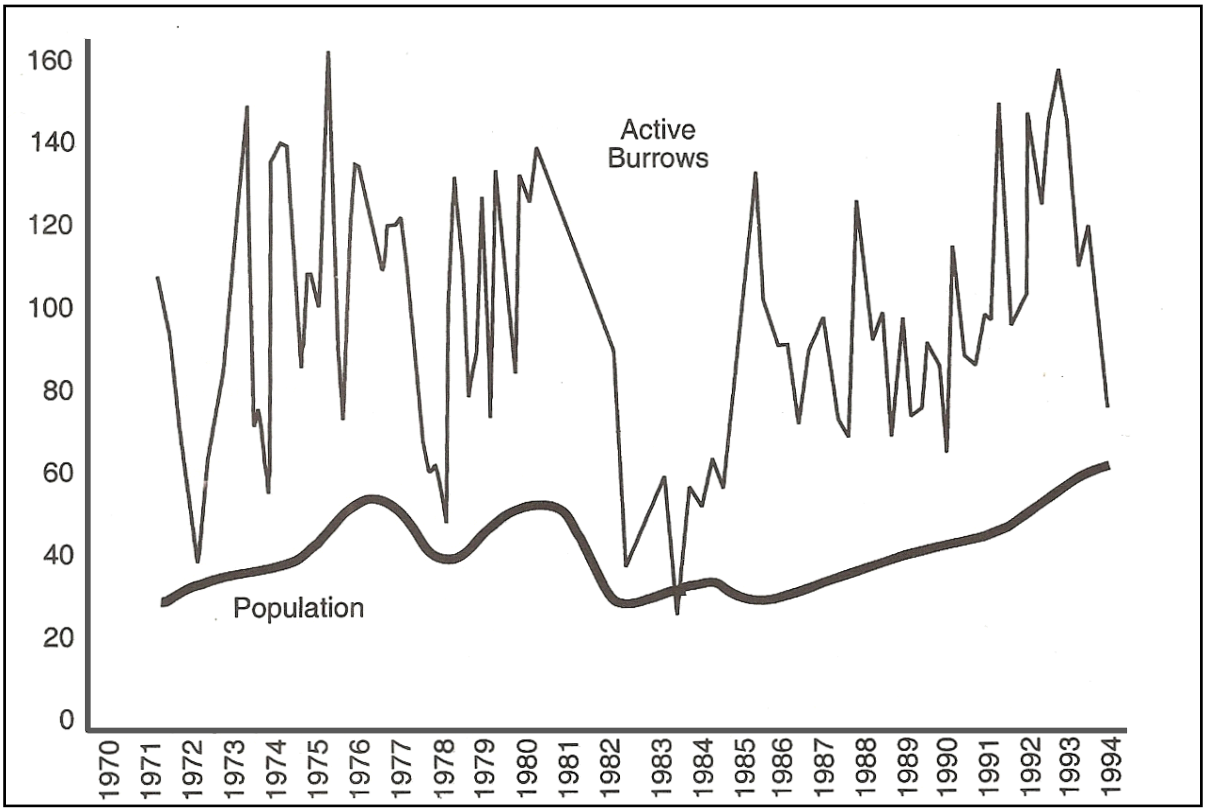


*Figure 10: The relationship between the number of wombats and the number of active burrows at Moorunde Wildlife Reserve near Blanchetown in the Murraylands (from Taylor 1998).*

A third methodology was applied by Koenig *et al.* (2012) in a survey near Swan Reach in the Murraylands. Motion cameras were placed at the entrances of 21 warrens, and wombats were photographed entering and leaving. An average of 0.5 wombats per active burrow was observed. However, this figure varied from 0.35 in clay to 1.27 in sheet calcrete soils;

suggesting that a single index may be an oversimplification and different figures may be required based on local conditions. These variations between soil types can be exacerbated by other factors such as grazing competition and predation, with significant differences in population density being noted on either side of the dingo fence (~ 0.2 animals / active burrow in areas where dingoes were present) (Sparrow 2013).

An important consideration in regard to all the indices of wombats per active burrow is that they have been based on limited data from a limited number of areas. Tiver's mark / recapture method only encompassed eight warrens in each of two locations, and Koenig *et al.* camera survey covered 21 warrens in one location. Given these limitations, there is a strong case for further research in this area, including in other survey regions.

**Population estimates**

Table 1 lists all the size estimates which have been made of the various population groups:

*Table 1: List of all L. latifrons population estimates conducted to date.*

| Year | Estimate | Source |
|---|---|---|
| **Nullarbor Plain (outside the dog fence)** | | |
| 1986 | 109,051 | NPWS (from St. John 1998) |
| **Nullarbor Plain (inside the dog fence)** | | |
| 1980 | 162,854 | Tiver (1980) |
| 1995 | 457,000 | Biggs *et al.* (2002) |
| 2002 | 476,100 | Biggs *et al.* (2002) |
| **Murraylands** | | |
| 1981 | 30,636 | Tiver (1981) |
| 1992 | 33,871 | MacGregor and Wells (1998) |
| 2012 | 148,448 | Taggart and Ostendorf (2012) |
| **Eyre Peninsula** | | |
| 1989 | 9,502 | NPWS (from St. John 1998) |
| **Gawler Ranges - Lake Harris** | | |
| 1988 | 1,633 | NPWS (from St. John 1998) |
| **Gawler Ranges - Lake Acraman** | | |
| 1985 | 12,740 | NPWS (from St. John 1998) |
| **Yorke Peninsula** | | |
| 2009 | 830 | Sparrow *et al.* (2010) |

These estimates highlight a number of key issues:

- There have been no population estimates since the 1980's of the Nullarbor Plains outside the dog fence, Eyre Peninsula, or Gawler Ranges groups.
- There has been no attempt to estimate the number of wombats in Western Australia.
- The only two groups for which there have been more than one population estimate - and hence the potential for determining any trends - are the Nullarbor Plains inside the dog fence and the Murraylands.
- While there have been several population estimates of the Nullarbor Plains inside the dog fence, there have been none for twelve years.
- In the two regions where more than one population estimate has been made, the more recent estimates are substantially higher than the original estimates.

The results for both the Murraylands and Nullarbor Plains populations suggest that both groups experienced a significant growth period; the Nullarbor Plains from 1980 to 1995, and the

Murraylands from 1992 to 2012. However, the accuracy of both of these apparent trends bears closer consideration.

All of the available information suggests that an increase in the size of the population for the Nullarbor Plains group inside the dog fence is likely (Sparrow *et al.* 2011). While a 280% increase between 1980 - 1995 is possible, such a large increase in a geographically constrained area seems unlikely, especially given that a major drought occurred in the area in 1982/83 (Gibbs 1984), which would have had an impact of the wombat population. While adult wombats are generally able to survive drought conditions (Gaughwin *et al.* 1984), recruitment is significantly affected (Gaughwin *et al.* 1998). This suggests that there could be issues with one or both of these estimates.

This discrepancy in the trend data and the lack of more recent information is a concern. All the evidence suggests that the distribution is expanding and that wombats are a major problem for farmers and graziers in the area (Stott 1998). The lack of up to date information on which to base any management decisions is a cause of frustration in the community, and all stakeholders agree that more research is urgently required to understand the scope of the issue (Sparrow *et al.* 2011).

The apparent four-fold increase for the Murraylands population is also questionable. The region experienced below average rainfall for much of the period (the 'millennial drought' from 1997 – 2011) (Heberger 2012) and over the past few years many wombats in the area have been suffering from a debilitating disease syndrome attributed to potato weed (*Heliotropium europaeum*) (Woolford *et al.* 2014). An increase in the size of the population in the region is also contrary to the findings from a small area study conducted at Kooloola Station near Swan Reach (Taggart, D. A., Campbell, L. C., Finlayson, G. R., Sparrow, E., Steele, V. R., Dibben, R., Dibben, J., Dibben, I., Ostendorf, B, and Temple-Smith, P. D., unpub. data). Despite this, it is important to note that the 2012 survey included a much larger area, so a direct comparison between the two population counts is not valid. Given that the 1981 and 1992 surveys did not include the area to the north of the Morgan-Eudunda Rd, and this area is known to contain numerous colonies of wombats, this issue warrants further research to resolve the discrepancy in the population trend data for the region.

*Broad scale vs fine scale population surveys*

There have been two long term studies of small area populations in the Murraylands; Kooloola Station, and Moorunde Wildlife Reserve (Taylor 1998). Kooloola Station has been used as a field research site by the University of Adelaide since 1993. While the studies have focussed on a variety of topics, records were also kept of the numbers of wombats that were captured or observed during spot-lighting surveys. This has provided two important findings. Firstly, wombat activity varies seasonally, with higher levels of activity during winter and spring (Finlayson et al. 2010). Secondly, the population at Kooloola appears to have been in long term decline, with a consistent reduction in the number of wombats observed between 1993 - 2011 (Figure 11). This contradicts the estimated four-fold increase for the region as a whole, but whether these differences are due to local factors, or whether there are errors in one or both population trends, cannot be determined from the available information.

The evidence from the long-term study of Moorunde Wildlife Reserve (Taylor 1998) suggests that the wombat population experienced an overall increase between 1971 and 1994, notwithstanding a slight decrease which occurred during the 1980s due to drought (Figure 10). This trend appears to have been ongoing, with the latest estimates suggesting that the population on the reserve has increased from around 150 wombats in 1968, to between 500 – 600 in 2015 (Taylor 2015). This three to four-fold increase is consistent with the overall population trend data for the Murraylands region as a whole, but is contrary to the decline observed at Kooloola. While Kooloola and Moorunde are located within 20 km of each other in the same region and have similar ecosystems, the contrasting population trends over a similar period are most likely explained by different land-uses. Although Kooloola has been used for wombat research for over 20 years, it has remained an active sheep grazing property, with stocking rates varying over the period. On the other hand, Moorunde was converted to a protected area in 1968, and all livestock and other commercial activity were removed. Consequently, although the different land-use patterns mean that the population trend data cannot be directly compared, it could provide a useful model to contrast the effects of land-use and grazing competition from livestock on wombat population trends, and research is encouraged in this area.

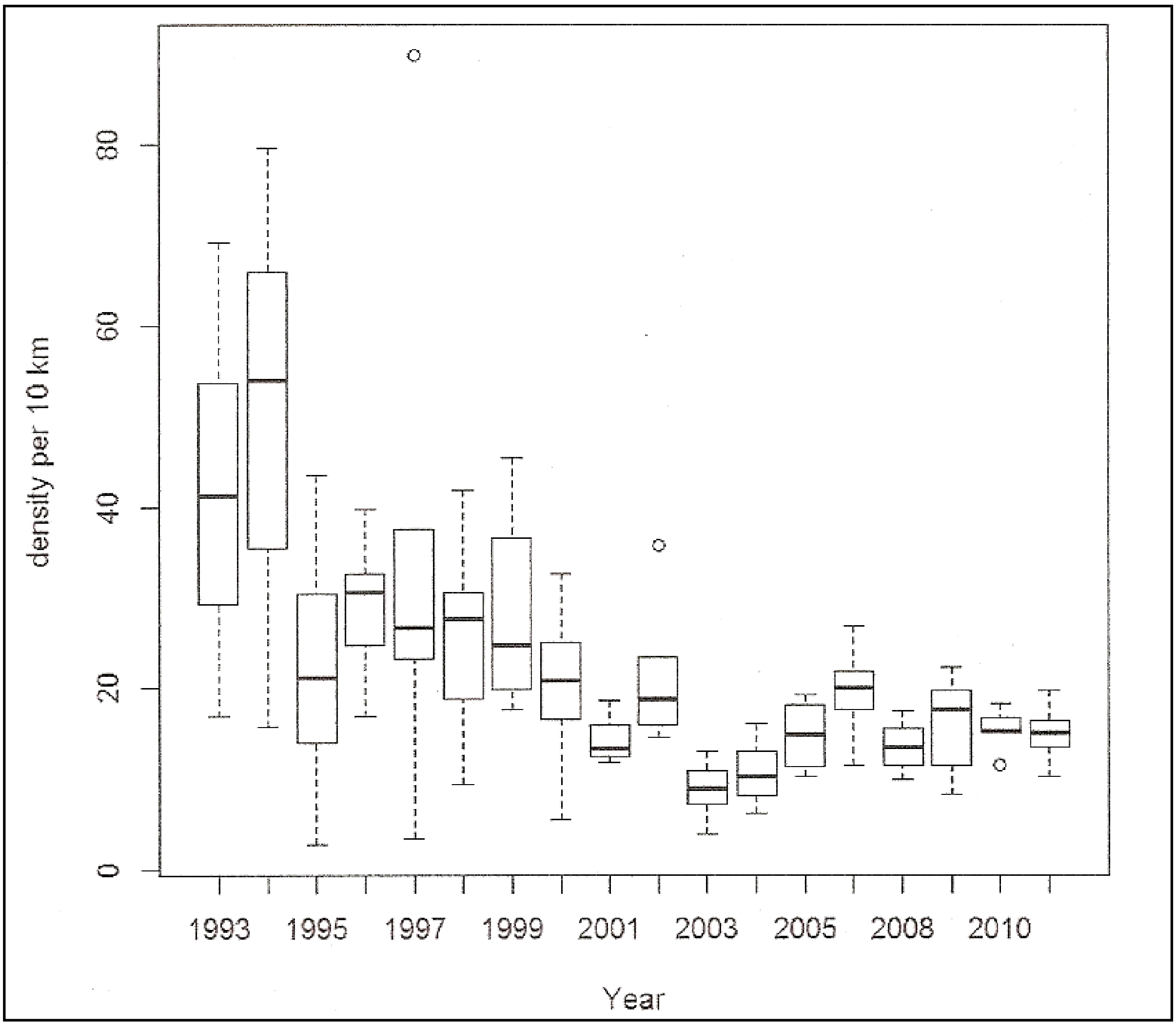


*Figure 11: Box and whisker plot of the number of wombats observed while conducting research at Kooloola Station near Swan Reach in the Murraylands between 1993 - 2011 (Taggart et al. unpub. data). The trend in population numbers appears to be negative, which contradicts the estimated fourfold increase in the overall population in the Murraylands over the same period calculated in Taggart and Ostendorf (2012).*

## Conclusions and recommendations for further research

Although research into the southern-hairy nosed wombat population began in the 1970s, there is still a great deal that we do not know about the species – especially in regard to their species-wide distribution and abundance. While some regions such as the Murraylands have been subjected to ongoing research, others, such as the Gawler Ranges, Eyre Peninsula, Nullarbor Plains outside the dog fence, and Western Australia have been the subject of few studies. As a consequence, we know little about what has occurred in those areas over the past 30 years, and these should be priority areas for further research. Given the claims which have been made by the agricultural community about wombat population trends and the need for better information to guide management actions, urgent action is required to address these deficiencies in our knowledge. Even in the areas which have been well studied, there are discrepancies in the population trend data which need to be resolved.

Estimates of southern hairy-nosed wombat numbers have necessarily been based on indirect indices such as counting the number of active burrows and converting this into a total population count based on the number of animals per active burrow. Unfortunately, there has been only limited research undertaken to understand the fine details of these indices. As a result, some of the underpinning assumptions and basic knowledge of wombat population dynamics may be flawed, particularly the number of wombats per active burrow. Therefore, research needs to be undertaken to develop accurate indices which can properly inform the census process. This should include gaining a better understanding of how to assess whether or not a burrow is active, and how the number of wombats per active burrow varies based on seasonal and local environmental conditions.

The fragmented nature of the wombat distribution also begs a number of questions that should be the subject of further research. This should include, as a minimum: the likely distribution at the time of European settlement and how that has changed over time; the factors which caused the population to fragment; the environmental and anthropogenic factors which influence local area abundance; and the bioclimatic and other factors which determine both the fundamental and realised environmental niches.

Finally, a great deal of data on southern hairy-nosed wombats is contained in unpublished manuscripts, reports and studies, and this review has had to draw heavily upon these for completeness. Further work is therefore encouraged towards submitting this information for publishing in journals, to ensure its widest possible dissemination, accessibility and review by other wildlife researchers.

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# Statement of Authorship

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# Chapter 2: Historical changes in the distribution of hairy-nosed wombats (*Lasiorhinus* spp.): a review

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**Abstract**

*We conducted a search of the historical records for any mention of hairy-nosed wombats in order to establish their likely distribution at the time of European settlement. The evidence suggests that there were two main groups of southern hairy-nosed wombats (Lasiorhinus latifrons) that were separated by Spencer Gulf in South Australia (SA). The western group extended to Balladonia in Western Australia (WA), while the eastern group extended along the Murray River to Euston in New South Wales (NSW). The Queensland population of northern hairy-nosed wombats (L. krefftii) was geographically large but highly patchy, and there was an abundant population in the NSW Riverina. Both species experienced a population decline between 1870 – 1920, with the main influences thought to be competition from rabbits and control actions by landholders. Our findings suggest that the ongoing control of rabbits via methods that do not harm wombats is critical for wombat conservation today. We also suggest that hairy-nosed wombats may be sensitive to climate change, and recommend more research on this topic.*

## Introduction

Over the past 200 years, the influences of European settlement have fundamentally transformed the Australian landscape. Land clearance has altered the habitat of many species, and the native vegetation that remains is fragmented into a patchwork of different sizes and shapes with few connecting corridors. Introduced herbivores such as rabbits and goats, and predators such as dogs, foxes and cats have radically changed the trophic order. As a consequence, some native species have gone extinct, with others being threatened because of habitat loss, grazing competition and predation by feral species (Morton 1990).

The three vombatidae species – *Vombatus ursinus* (common wombat), *Lasiorhinus krefftii* (northern hairy-nosed wombat) and *L. latifrons* (southern hairy-nosed wombat) have all been affected by these changes. The distribution of the common wombat is generally contiguous, although somewhat patchy, in suitable habitat along the ranges from southern Queensland to south-eastern Victoria, with additional population groups on Flinders Island, in Tasmania, and in the southern border region between Victoria and SA (McIlroy 1995). However, the distribution of the two hairy-nosed wombat species is highly fragmented. There are six distinct sub-population groups of southern hairy-nosed wombats in SA (St John 1998) and one translocated colony on Wedge Island at the entrance to Spencer Gulf (Copley 1994). Northern hairy-nosed wombats are restricted to a single colony in Epping Forest National Park in central Queensland (Crossman *et al.* 1994); although a translocated colony has recently been established in part of its former range near St George in southern Queensland (White *et al.* 2014) (Figure ).

The timing and causes of the fragmentation in the distribution of hairy-nosed wombats are poorly understood. Some have suggested that the distribution of the southern hairy-nosed wombat may have been continuous in SA from the Murray River to the Western Australian border and beyond prior to European settlement (Wood-Jones 1925; St John 1998). Three population groups of northern hairy-nosed wombats are known to have existed – in the NSW Riverina, at St George in southern Queensland and in Epping Forest in central Queensland (Crossman 1988). This has led to the suggestion that the distribution of this species may have been continuous from southern NSW to central Queensland when Europeans arrived in Australia (Horsup and Johnson 2008) (Figure 1). However, these hypotheses have not been tested. The Queensland populations of northern hairy-nosed wombats did not come to wider attention until the twentieth century (De Vis 1900; Morning Bulletin 1937), and the first detailed assessments of the distribution and abundance of southern hairy-nosed wombats were not undertaken until the 1970s (Aitken 1971, 1973).

Establishing the true distribution and the timing and causes of any changes are important for wombat conservation today, because if incorrect assumptions are made any management actions taken may be counter-productive. One way this can be done is to examine the historical record for reports and stories of hairy-nosed wombats. This study reviews this record with the aim of determining the likely distribution both prior to, and at the time of, European settlement.

The timing of any changes to that distribution was also examined in order to establish the possible causes.

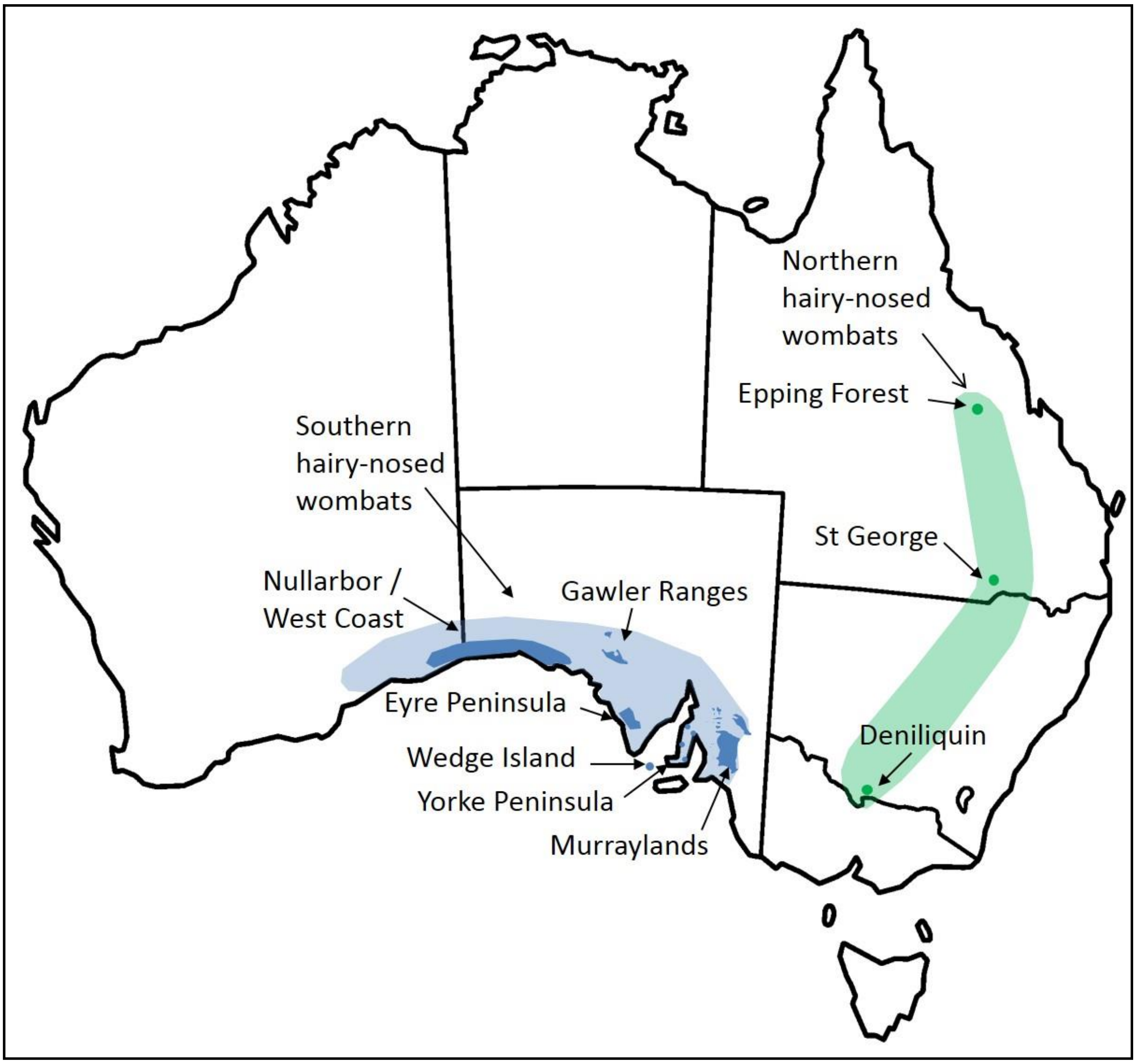


*Figure 1: Current (dark colour) and extrapolated (light colour) distribution of hairy-nosed wombats. Although the extrapolated distribution has been widely accepted as representing the likely distribution at the time of European settlement, it is based more on conjecture than any definitive evidence.*

**Methods**

We conducted a literature search of journals, government reports, museum records, the diaries and maps of the early explorers, and newspaper articles for any mention of hairy-nosed wombats. The National Library of Australia on-line data-base 'Trove'

(<http://trove.nla.gov.au/>) was used as the primary source for newspaper articles. All reports were collated in a Microsoft Access database and their locations mapped.

**Southern hairy-nosed wombats: historical distribution and history of population change**

Although it has been suggested that southern hairy-nosed wombats were first described from remains before they were encountered by European settlers near Swan Reach in the late 1840's (Wood-Jones 1925), this is not entirely true. Wombats were known in the Adelaide area at the time of European settlement in 1836 (The South Australian Advertiser 1862; Adelaide Observer 1890). They were also found throughout other parts of SA in the years immediately following (Allen 1839a, 1839b; Eyre 1846). What is true is that initially no distinction was made between the southern hairy-nosed wombats of SA and the common wombats that had been encountered in the eastern Australian colonies. The fact that an extant wombat species may have existed which was different to the common wombat was first realised in 1845 from the examination of a skull which was supplied by the Governor of SA, George Grey (Owen 1845). However, it was not until 1861 that the existence of this species was confirmed from the description of a living southern hairy-nosed wombat in the Adelaide Botanical Gardens (Angas 1861).

Many of the early reports of southern hairy-nosed wombats were from areas outside their current distribution, which provides the first definitive evidence that the distribution has changed since European settlement. We collated and mapped these reports and compared them to the regions where wombats are currently located to determine how the distribution has changed over time.

*Adelaide Plains and the Adelaide Hills*

After the settlement of Adelaide in 1836, the new European colony expanded rapidly to the north and into the hills to the east. Wombats were encountered in the vicinity of the new city of Adelaide and in virtually all of the surrounding areas (Figure 2). In the hills to the east and south they were found in areas such as Woodchester (South Australian Chronicle and Weekly Mail 1880), Hope Valley (South Australian Register 1872) and Strathalbyn (Southern Argus 1897). Indeed, wombats were so numerous in the hills to the south-east of Adelaide that in the late nineteenth century the area around Strathalbyn 'between Bletchley and Belvidere' (Strathalbyn Naturalists Club 2000) was colloquially known as 'Wombat Plains' (Chronicle

1937). To the north of Adelaide between Gawler and Port Wakefield wombats were encountered and their burrows were filled in to build roads and other infrastructure (The South Australian Advertiser 1859). They were also found in the Barossa and Clare Valleys (The South Australian Advertiser 1861; South Australian Register 1898).

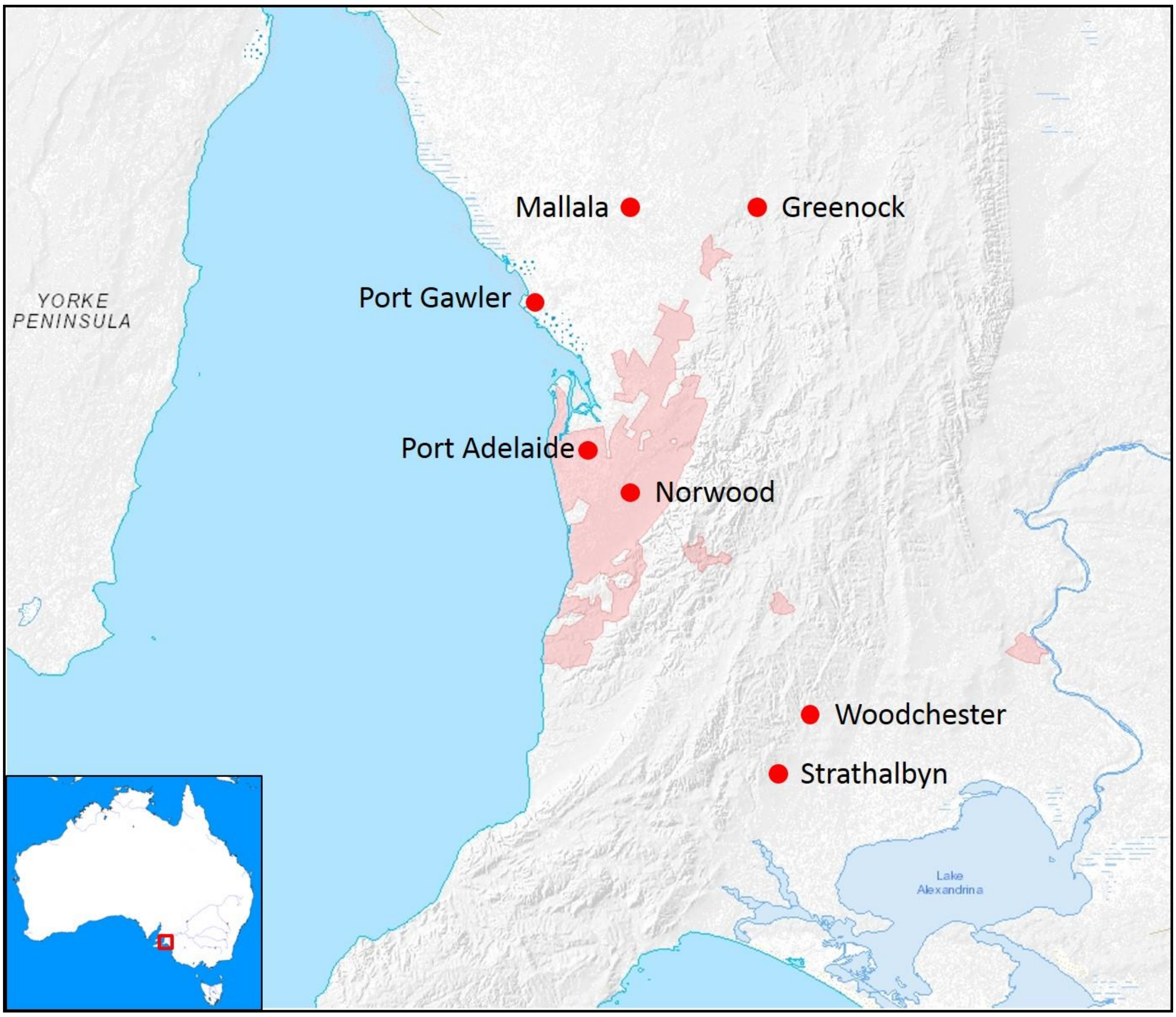


*Figure 2: Reported locations of southern hairy-nosed wombats in Adelaide and the surrounding areas during the nineteenth century.*

No wombats are found in any of these locations today. The exact date of their disappearance is difficult to determine, but even as early as the 1860s wombat sightings in the vicinity of Adelaide were rare (The South Australian Advertiser 1862), and their presence in the region was consigned to living memory by 1890 (Adelaide Observer 1890). In the Adelaide Hills and around Strathalbyn, wombat burrows were being described as abandoned and were occupied by rabbits prior to the turn of the century (Southern Argus 1897). Whilst it is difficult to provide exact reasons for the decline and disappearance of wombats from the Adelaide region, there is little doubt that they were subjected to a deliberate campaign to exterminate them from some areas (The South Australian Advertiser 1878). As a consequence, it would appear that the most likely cause of their demise was spread of human settlement, and competition from rabbits which were already considered to be a significant pest in the region by the 1870s (Northern Argus 1873).

*Murraylands*

Wombats were encountered on the flats of the Murray River valley to the east of Adelaide as the settlement expanded during the 1840s (South Australian Chronicle and Weekly Mail 1877). Reports indicate that the wombat population extended from south of Mannum, north to Morgan on the north-west bend of the river (The Sydney Morning Herald 1862; The Register-News Pictorial 1929), and eastwards along the northern banks of the Murray River into NSW (Australian Town and Country Journal 1885a).

Shortly after, coincident with the arrival of rabbits in the area, the wombat population in the district underwent a precipitous decline (Adelaide Observer 1887). By the 1920s it had contracted to a core area from just south of Swan Reach to Blanchetown (The Register-News Pictorial 1929). The numbers of wombats had declined to the point where sightings were rare, and some thought that they were doomed to extinction altogether (Murray Pioneer and Australian River Record 1920). However, wombats continued to survive in the core area to the west of the river and across the river plains to Sedan. Despite their numbers being estimated to be much lower than at the time of European settlement, farmers in the area still considered them to be pests and undertook actions to control them, such as fumigating and bulldozing their warrens (The Advertiser 1950).

By the time the first broad-scale wombat population survey of the Murraylands was conducted in 1981 (Tiver 1981), the population appears to have undergone a slight recovery in the northern and western regions of the district. The geographic extent was found to be bounded to the east by the Murray River, westwards by the Sedan Hills, and from just south of Swan Reach, north to Morgan. A second broad scale survey was conducted in 1992 (MacGregor and Wells 1998) following a major drought that occurred in the area in 1982/83. The report highlighted the sensitivity of the population to drought, as the distribution had contracted along the borders and consolidated in the centre, with higher densities along the Murray River between Blanchetown and Swan Reach. This is the same core area that the population had contracted to in the first half of the twentieth century (Figure 3).

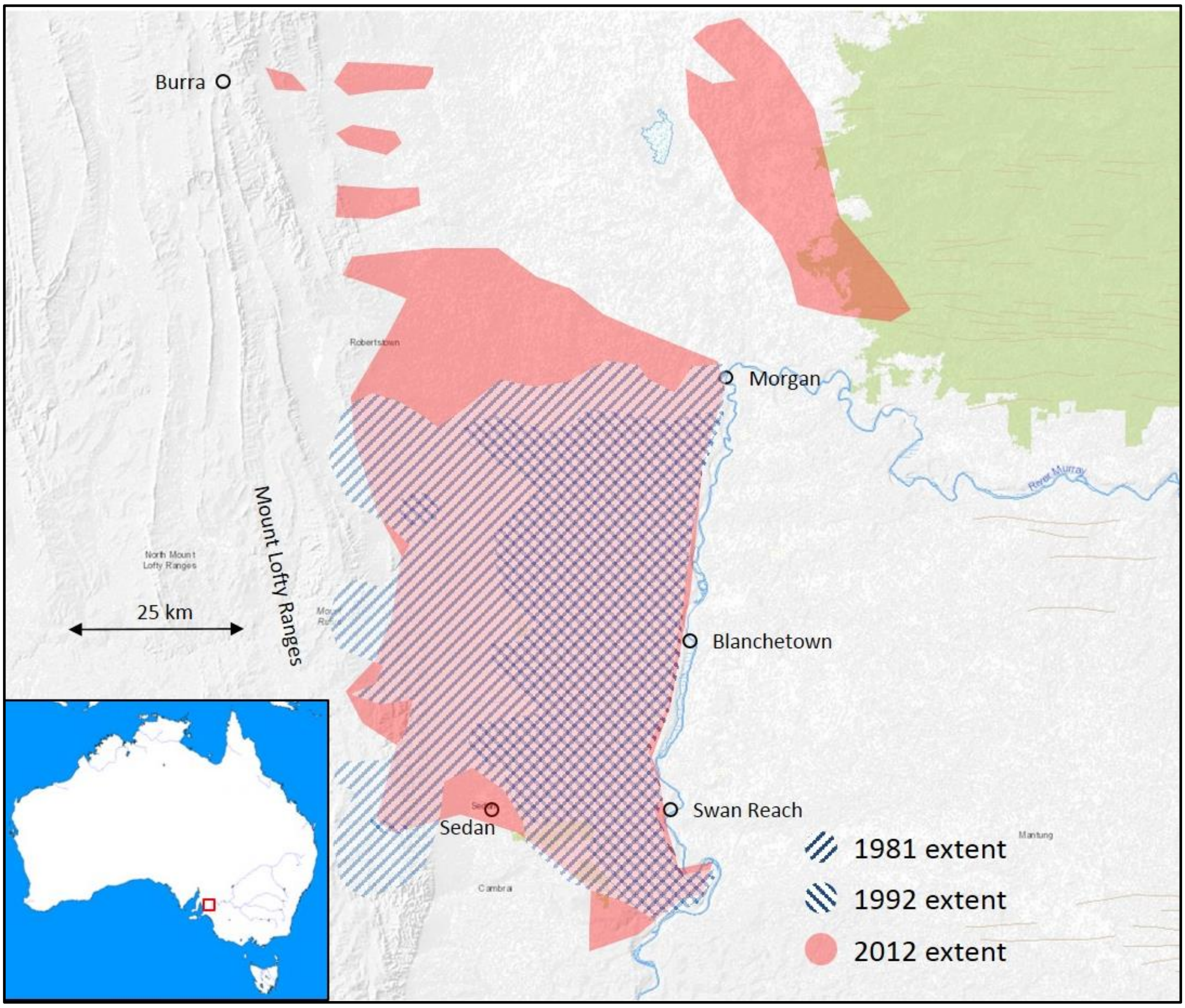


*Figure 3: Distribution of southern hairy-nosed wombats in the South Australian Murraylands, showing changes from 1981 – 2012.*

The most recent broad scale survey was conducted in 2012 (Ostendorf and Taggart unpub. data). The findings suggest that the population had returned to its 1981 extent and had increased its distribution to the north-west by ~ 30 km. There were also several fragmented groups of wombats stretching a further 30 km north along the foothills of the Mount Lofty Ranges, and a large population on the northern side of Burra Creek (Figure 3). Unfortunately, whether these additional population groups were present in 1981 cannot be determined as these areas were not included in the 1981 or 1992 surveys.

Whilst the latest distribution survey also suggested that wombat numbers had increased over the previous 20 years (Ostendorf and Taggart unpub. data), this is contrary to other data from the region. Two droughts had occurred in the area during the previous 20 years (2002/03 and 2006/07), and many wombats in the area have been suffering from a debilitating disease syndrome attributed to a lack of native grass species and a dietary switch to introduced weed species high in toxins (Woolford *et al.* 2014). An increase in the size of the population is also contrary to evidence gathered from Kooloola Station near Swan Reach, which suggests that this population has been in long term decline since the mid 1990's (Taggart *et al.* unpub. data). This apparent discrepancy in the estimates of overall abundance highlights the difficulties in accurately ascribing causal effects to wombat population dynamics. Consequently, further research is strongly recommended to develop a reliable means of assessing wombat population abundance and trends.

*Along the Murray River*

The eastern edge of the current distribution of southern hairy-nosed wombats is near the South Australian town of Morgan, which is located where the river turns south after flowing westwards for most of its length (the 'north-west bend'). However, during the nineteenth century there are several reports of wombats occurring along the Murray River in the area between Morgan and Euston in southern NSW (Geelong Advertiser 1860; Australian Town and Country Journal 1885a). This is approximately 300 km to the east of the current distribution. The Euston animals also appear to be restricted to the north side of the river (The Courier 1862) and are described as being different to the 'common' wombats found in Victoria (Geelong Advertiser 1860). However, by the early twentieth century the presence of wombats in this region is described as 'being in the past' (The Mildura Cultivator 1914) and no trace of them remains today.

*Yorke Peninsula and the mid-north*

Some of the initial reports of southern hairy-nosed wombats were made by explorers who were surveying the coast and regions close to Adelaide soon after settlement in 1836. Wombats were said to be numerous on the eastern shores of Yorke Peninsula near where Port Vincent now stands (Allen 1839a) and in the centre of the peninsula near Maitland (Kapunda Herald 1882) and Minlaton (Observer 1908). Further to the north in the vicinity of Wallaroo and Kadina, wombats were described as 'countless' (South Australian Weekly Chronicle 1861) (Figure 4).


*Figure 4: Reported locations of southern hairy-nosed wombats on the Yorke and Eyre Peninsulas in the nineteenth century.*

To the north of Yorke Peninsula in the mid-north of the state, reports of wombats from the nineteenth and early twentieth century are scarce. Several reports have been noted from the southern part of the region at locations such as Snowtown (Kapunda Herald 1908), and Burra (Burra Record 1951), with the most northerly report being from the southern Flinders Ranges (Kapunda Herald 1881). This suggests that, although wombats were present in some parts of the mid-north of SA from the Clare Valley north to the southern Flinders Ranges at the time of European settlement, they were not considered noteworthy and their distribution was probably quite patchy.

Initially at least, wombats were not considered to be pests on Yorke Peninsula as they played an important role in the development of the economy in the area. The discovery of copper in what is now the 'Copper Triangle' – the towns of Kadina, Moonta and Wallaroo – was attributed to a wombat excavating copper ore while digging its burrow. Indeed, so revered were wombats by the copper miners that they were 'exempted from the hostile attack of gun and dog', one of the largest copper mines in the area was named the 'Wombat Mine', and the hotel in Kadina used by miners was named the 'Wombat Hotel' in their honour (South Australian Weekly Chronicle 1861). This changed with the arrival of rabbits in the area (The South Australian Advertiser 1879) and the more extensive use of the land for cropping (Adelaide Observer 1901). Rabbits were deliberately introduced in the mid-north of SA at Kapunda in 1857-58 (Peacock and Abbott 2013), and established themselves so quickly that by 1873 residents in the area petitioned parliament for legislation to destroy them (Kapunda Herald and Northern Intelligencer 1873). Wombats were now considered to be a nuisance (Kadina and Wallaroo Times 1925) and wombat burrows were destroyed in order to control rabbits (The Advertiser 1905).

By the first half of the twentieth century sightings of wombats on the Yorke Peninsula were rare, and they had disappeared from many parts of the region entirely (The Register 1925). The most recent assessment of the distribution of wombats on Yorke Peninsula put their numbers at less than 800 individuals, which were scattered between fragmented colonies, 80% of which contained less than 20 individuals (Sparrow *et al.* 2010). Most of the mid-north is now thought to be wombat free, except for isolated colonies to the north-east of the Clare Valley in the vicinity of Burra (Ostendorf and Taggart unpub. data) where they appear to have persisted in low numbers throughout the twentieth century (Burra Record 1951). A colony also exists near Black Rock in the southern Flinders Ranges (Jenny Mannion, pers. comm. 20 October 2015), although it is thought that these animals may be the descendants of a deliberate release program.

*Eyre Peninsula*

Southern hairy-nosed wombats were encountered on Eyre Peninsula shortly after the settlement of SA, with reports of wombats being abundant in locations over much of the southern half of the peninsula. These include the west coast from Port Lincoln (Allen 1839b) to Streaky Bay (The Advertiser 1890), the east coast as far north as Cowell (Chronicle 1933), and in the interior at locations such as Cleve (Chronicle 1945) and Mount Wedge (Eyre 1846). No reports could be found of wombats in the north-eastern region of the peninsula between Whyalla and Port Augusta, suggesting that they may have been absent from the area at the time of European settlement (Figure 4).

By the turn of the century wombat numbers had declined dramatically along the east coast of the Eyre Peninsula (West Coast Sentinel 1944), and they appear to have disappeared entirely from the Port Lincoln area (Port Lincoln Times 1942). By the time the first serious efforts were made to establish their likely distribution in the region (Aitken 1971) they had contracted to a core area along the western side of the peninsula to the south of Venus Bay, bounded by the Kulliparu, Cocata, Barwell and Bascombe Well Conservation Parks.

The decline in wombat abundance in the region has been blamed by some on rabbits (Port Lincoln Times 1934), and this is likely given the impact they have had on common wombats in other locations (Cook 1998; Bird 2012). In 1888 the plague of rabbits on western Eyre Peninsula was considered to be the worst in the state (Stodart *et al.* 1988). Today, the majority of the peninsula is devoted to cropping, with the current distribution of wombats mainly restricted to areas used predominantly for grazing. Surveys of farmers and graziers across the state suggest that while they will use strong measures to control wombats on cropping land, they are generally tolerated on grazing land and any control actions used against them will be less severe (Sparrow *et al.* 2011). This suggests that land clearance and control actions by farmers may also have been important in the decline of wombats in this region.

The likely distribution of southern hairy-nosed wombats on the southern Eyre Peninsula in the mid-nineteenth century raises an intriguing possibility about their overall distribution. If wombats were absent from the region between Whyalla and Port Augusta, and from the area between the Clare Valley and Port Augusta on the eastern side of Spencer Gulf, this means that there would not have been any linkages between the wombats on the Eyre and Yorke Peninsulas. In effect, the population of southern hairy-nosed wombats would have already been fragmented at the time of European settlement; with one major group to the west and one to the east of Spencer Gulf.

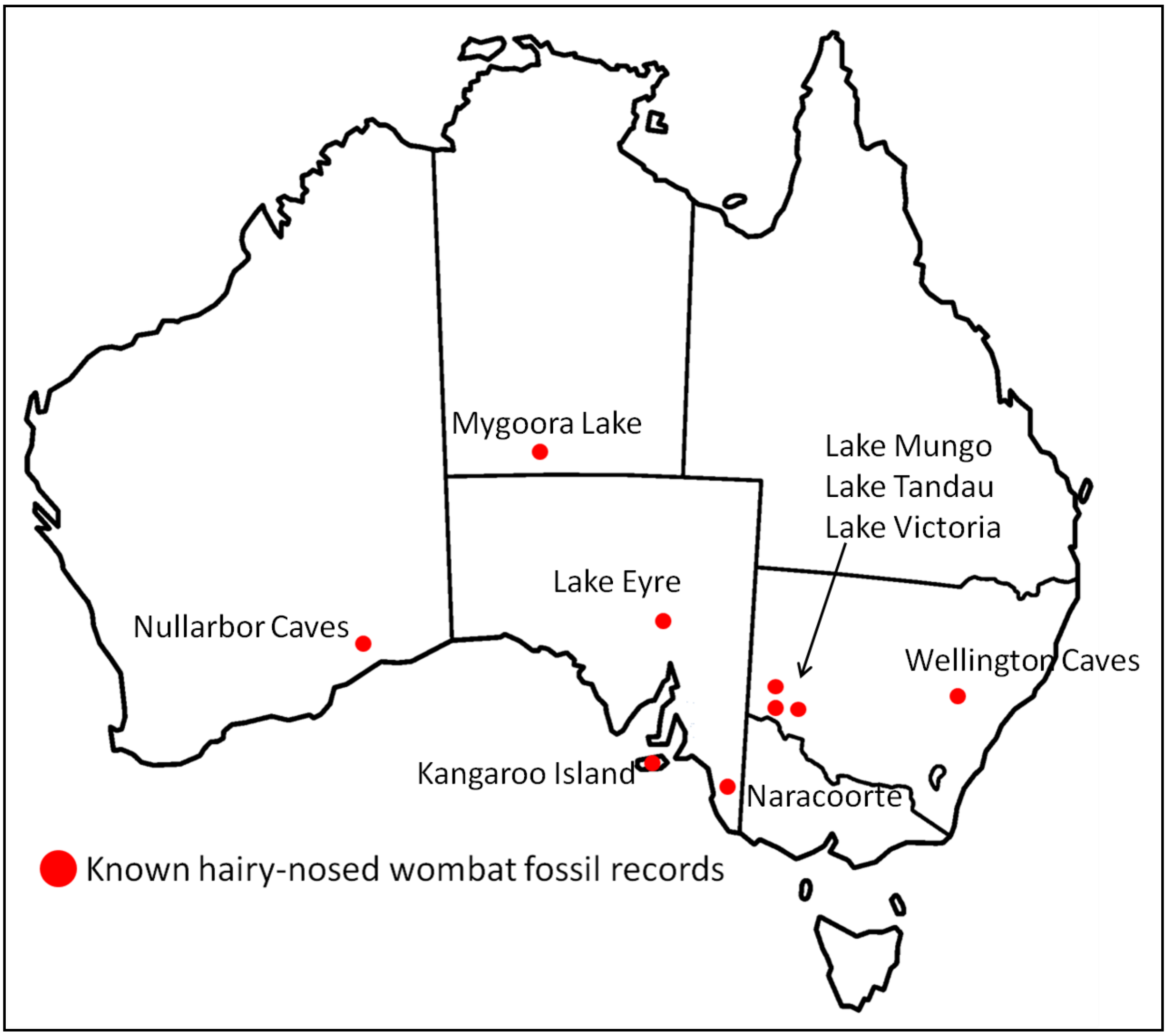


*Figure 5: Locations of fossil remains of hairy-nosed wombats.*

It is possible that this division could have arisen as a result of paleoclimatic changes in the region. Hairy-nosed wombats remains from the late Pleistocene / early Holocene have been found at numerous sites across what is now the arid and semi-arid interior including; Lake Eyre (SA) - 50,000 YBP [years before present]; Lake Mungo (NSW) - 19,030 YBP; Lake Tandou (NSW) - 12,350 YBP; Mygoora Lake (NT) - 12,100 – 9,300 YBP; Lake Victoria (NSW) - 6,360 YBP; and Lake Mulurulu (NSW) – undated (Hope 1978; Megirian *et al.* 2002; Webb 2009) (Figure 5). Prior to ~ 10,000 YBP, Spencer Gulf was a broad river valley, which would have provided a land bridge between the Yorke and Eyre Peninsulas. However, rising sea levels following the last glacial maximum gradually flooded the area until they peaked at their current level ~ 6,400 YBP (Belperio *et al.* 2002). Then from ~ 4,500 YBP a decline in winter rainfall caused a decline in grasslands and an increase in chenopod scrublands (Singh and Luly 1991) in the semi-arid interior of the region. This would not have favoured hairy-nosed wombats, and it is possible that their distribution contracted away from the interior towards the more favourable vegetation communities and rainfall regions that now predominate across the south-central areas of the state. As a consequence of both this range contraction and the rising seas flooding Spencer Gulf, the distribution would have been split into two main population groups to the east and west of the gulf. This hypothesis is supported by genetic analysis of the extant sub-population groups (Alpers *et al.* 1998). Whilst genetic differences were found between each of the current sub-population groups, the greatest differences were found between those on the eastern and western sides of Spencer Gulf, suggesting that they probably became isolated from each other at an earlier date.

*Nullarbor Plains and the west coast*

The population of hairy-nosed wombats on the Nullarbor Plains and west coast is the largest and most geographically diverse group which exists today, with sections on either side of the dog fence and on agricultural land, crown land, protected areas and Aboriginal lands. It is also the most extensively surveyed, with broad area assessments being conducted in 1973 (Aitken 1973), 1980 (Tiver 1980), 1986 (St John and Saunders 1989), 1995 and 2002 (Biggs *et al.* unpub. data).

A consistent theme across all surveys is that the distribution of wombats in the area has been expanding since the 1960s. In 1973 the western edge extended to near Eucla on the Western Australian border, with isolated colonies as far as Mundrabilla, ~ 70 km further west. At the same time the eastern edge was near Bookabie (Aitken 1973). By the mid-1980s the western edge had consolidated and the eastern edge had extended by 30 km to near Penong (St John 1998). The 1995 and 2002 surveys found that the eastwards expansion had continued by an additional 20 km past Penong, with an increase in population density in the recently inhabited areas (Biggs *et al.* unpub. data) (Figure 6).

Prior to these surveys, the remote location and generally sparse European population meant that there were relatively few reports of wombats from the nineteenth and early twentieth centuries. However, it would appear that the eastern edge of the distribution in the late nineteenth century extended past Penong (Chronicle 1897) to at least Ceduna (West Coast Sentinel 1948), and probably extended further to join up with the Eyre Peninsula group. This is supported by the presence of an isolated population at Poochera on the northern Eyre Peninsula; approximately half-way between Ceduna and the current Eyre Peninsula population group (Figure 4). DNA analysis of this group exhibits genetic signs of isolation (Walker 2004), suggesting that it may be a remnant group which has been left behind, rather than a group which has recently dispersed to the area.

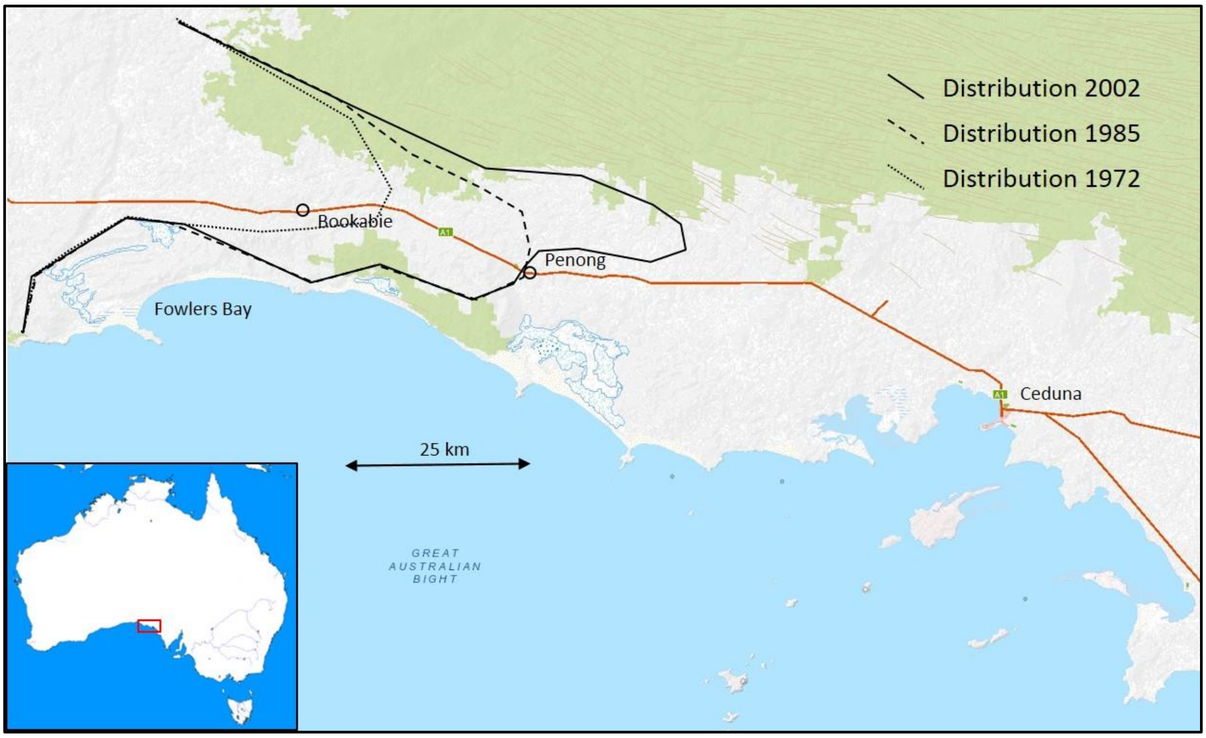


*Figure 6: Eastern edge of the distribution of southern hairy-nosed wombats on the far west coast of South Australia, showing expansion in range from 1972 – 2002.*

At the western edge of the main population group in the mid-nineteenth century, wombats could be found from Eucla in WA (The Advertiser 1893) to as far as Balladonia, ~ 400 km from the border (The Australasian 1918). It is unclear why the distribution should have terminated at Balladonia and not continue further into the south-west corner of WA. One possible explanation relates to the soils in the area. Balladonia is located at the western edge of the Nullarbor Plain calcareous soil region, with the areas to the south-west dominated by organosols (Isbell 2002). Southern hairy-nosed wombats are known to show a distinct preference for burrow construction in calcarosols, with up to 92% of all warrens in SA occurring in regions where the abundance of calcrete and regolith carbonate in the surface materials exceeds 90% (Marshall *et al.* unpub. data). Soil type appears to be a strong environmental predictor for potential southern hairy-nosed wombat habitats (Walker *et al.* 2007), and might therefore provide an explanation for their presence or absence from other areas which otherwise appear suitable.

Hairy-nosed wombats disappeared from WA soon after European settlement in the 1880s (The Daily News 1935). Whilst land clearance and persecution by graziers has been put forward as the main reason (Temby 1998), this is considered unlikely as the area between Balladonia and the South Australian border is generally used for marginal rangeland grazing (Beetson *et al.* 2001) or protected areas. Rabbits crossed the border from SA by 1894 and were considered to be a significant threat to grazing in the region throughout the first half of the twentieth century (Port Lincoln Times 1940). They had reached Balladonia by 1898, and this is likely to have had an impact on the wombat population. But whether rabbits were solely responsible for the wombat decline in the area, or whether it was a combination of grazing competition from rabbits, livestock, drought and control actions by graziers, cannot be determined.

*Gawler Ranges*

There is little information from the nineteenth and early twentieth century regarding the presence of wombats in the Gawler Ranges. De Vis (1900) refers to correspondence from the Director of the Adelaide Museum, Edward Charles Stirling, advising that the furthest north wombats could be found in SA was in the Gawler Ranges to the north-west of Port Augusta. A report from the first half of the twentieth century also suggests that wombats were numerous on parts of Wilgena Station to the north-west of Lake Harris in 1929 (The Register-News Pictorial 1929).

The only two detailed surveys of the region which were conducted in 1971 (Aitken 1971) and 1988 (St John 1989) located two main sub-population groups of wombats; one centred to the south and west of Lake Acraman and a smaller group on the western side of Lake Harris. Isolated colonies have also been located between these two main groups in the vicinity of Lake Everard, to the east near Lake Gairdner, and to the south in the Gawler Ranges National Park (St John 1998; Walker 2004). The Lake Harris group appeared to have been relatively stable and not to have changed significantly between the two surveys. The reason given for this was that the sandy soils to the south of the population appeared unsuitable for burrow construction, which would limit the potential for expansion (St John 1998).

Reports from graziers at the time of the initial survey suggested that the Lake Acraman group had increased in range by up to 30 km to the south and west since the early 1960s (Aitken 1971). A comparison of these data with a later survey conducted in 1988 showed that the distribution had continued to expand by a further 25 km towards the south-west, and had also spread to the north and east around the lake (St John 1998). This expansion in the latter half of the twentieth century suggests that it may have undergone an earlier decline similar to those experienced by other southern hairy-nosed population groups. However, in the absence of any evidence on their distribution in the nineteenth century, this remans conjecture only.

In 1988, the south-western edge of the main group near Lake Acraman was ~ 100 km from Streaky Bay on the Eyre Peninsula, with isolated colonies further to the south within the Gawler Ranges National Park (St John 1998). Whether the Eyre Peninsula and Gawler Ranges populations were connected at the time of European settlement could not be determined from reports of the physical location of wombats, but the possibility might be inferred from an assessment of the environment in the region.

The Gawler Ranges wombat population does appear to be expanding southwards into the Gawler Ranges National Park, with DNA analysis of a colony in the park suggesting it includes recent female arrivals (Walker *et al.* 2008). However, a series of dune-fields and playa lakes lies to the south of the Gawler Ranges National Park, suggesting that there may be limits on the ability of the population to expand towards the coast and link up with the wombats on Eyre Peninsula and the far west coast. Although there are isolated colonies between the two main groups and to the south of the Lake Acraman group, these are in small numbers only and consolidation with the more southerly population groups is considered unlikely (St John 1998).

Whilst the dune-fields and unfavourable vegetation may provide barriers against expansion today, this may not have been the case in the past. The climate and vegetation communities which existed in the Gawler Ranges in the early Holocene were likely to have been more favourable for hairy-nosed wombats (McCarthy and Head 2001. However, from ~ 4,500 YBP declining winter rainfall and increased drought frequency caused the replacement of the woodland and grassland vegetation communities with the sparse chenopod communities which exist today (Magee and Miller 1998). This suggests that the current population of wombats in the Gawler Ranges may have persisted in favourable habitat which has become isolated because of climatic and vegetation changes which occurred long before European settlement of the region.

*Kangaroo Island*

Although hairy-nosed wombats are absent from Kangaroo Island today, they were once present on the island. Remains have been recovered from several locations which reveal that they were present between 16,000 – 11,000 YBP (Hope *et al.* 1977), and possibly more than 40,000 YBP (Wells *et al.* 2006) (Figure 5). Whether they were present on the island more recently than this cannot be determined, as the paleontological evidence is inconclusive.

For most of the past 80,000 years Kangaroo Island was part of the mainland (Lambeck and Chappell 2001). It became separated ~ 10,000 – 9,000 YBP via the same sea level rise that flooded Spencer Gulf. This coincided with a significant change to the island's climate and vegetation, with open woodland and grasslands being replaced by closed canopy woodlands (Forbes *et al.* 2010). The new habitat would not have suited southern hairy-nosed wombats (Aitken 1971) and it is possible that these changes contributed to its local extinction.

Whilst hairy-nosed wombats have probably been locally extinct on Kangaroo Island for several thousand years, there have been attempts to reintroduce them. Finders Chase National Park, located at the western end of Kangaroo Island, was gazetted in 1919 especially for the protection, preservation and propagation of threatened species which were to be translocated from the mainland (The Advertiser 1919). The southern hairy-nosed wombat was considered to be one such species, and a number of translocations took place in the first half of the twentieth century. Although they were initially successful, all translocations ultimately failed for unknown causes (The Register-News Pictorial 1929; The Advertiser 1936; News 1945; The Mail 1950; Copley 1994).

*Other regions of South Australia*

Whilst the current and recent distribution of hairy-nosed wombats is confined to the northern and western side of the Murray River, there is evidence of them occurring in the south-eastern corner of SA and across the border into Victoria in the past. Numerous fossils which have been identified as *Lasiorhinus* spp. have been found in the Naracoorte Caves, ~ 100 km to the north of Mount Gambier (Reed and Bourne 2009). The main fossil assemblage found in Cathedral Cave at Naracoorte includes a fossil that was originally identified as *L. latifrons*, and has been dated to the mid-Pleistocene, ~ 280 – 160,000 YBP (Brown and Wells 2000). However, another analysis suggests that the assemblage may include an example of *L. krefftii* rather than *L. latifrons*, and dates the remains to between 528 – 206,000 YBP (Reed and Bourne 2009).

Examples of *V. ursinus* have also been recovered, and the descendants of these earlier common wombats are now present in the area while hairy-nosed wombats are absent.

**Northern hairy-nosed wombats: historical distribution and history of population change**

*New South Wales Riverina*

Whilst common wombats were known in NSW from around the first decade of the nineteenth century (Woodford 2001), the discovery of hairy-nosed wombats in NSW did not occur until the second half of the nineteenth century (The Courier 1862) with the opening up of the country in the Riverina district along the Murray River, mid-way between the east coast and the South Australian border. This area is approximately 500 km to the east of the current distribution of southern hairy-nosed wombats and approximately 1,000 km to the south of the northern hairy-nosed wombat population which existed near St George at the time.

Although hairy-nosed wombats are absent from the Riverina area today, they were abundant in the late nineteenth century. These wombats were said to be different to those found in Victoria and the mountain regions of NSW, being described as 'plains wombats' (Australian Town and Country Journal 1885*b*) and 'Riverina wombats' (The Australasian 1885). Although they were initially identified as southern hairy-nosed wombats because of their similarities to the wombats found in SA (Kershaw 1909), recent taxonomic and DNA analysis confirms that they were northern hairy-nosed wombats (Dawson 1983, Taylor *et al.* 1994).

The geographic extent of the Riverina population has been described as being limited to an area of ~ 55 km E/W x 25 km N/S, centred around the town of Jerilderie, ~ 70 km to the north-east of Deniliquin (Kershaw 1909) (Figure 7). As a result, whilst previous descriptions of the population of wombats in this region usually refers to them being located near Deniliquin, it is probably more correct to describe them as being from near Jerilderie, or more properly, as Riverina wombats.

In addition to this main population group, there are also reports of wombats and their burrows from Wakool, 80 km to west (Riverine Herald 1937), and along the Murray River near Barooga and Boomanoomana, 60 km to the south (The Australasian 1890; The Corowa Chronicle 1906) (Fig. 7). This suggests that the population may have occupied a geographically larger area than had been previously described; although it is possible that these reports are of isolated, satellite colonies that were located around a core area of high abundance. The wombats appear to have been restricted to the northern side of the Murray River, with reports from Barooga in NSW, but none from Cobram directly across the river in Victoria (The Australasian 1890). The number of wombats in the area was also quite large, being described as 'in the thousands' (Australian Town and Country Journal 1885*c*).

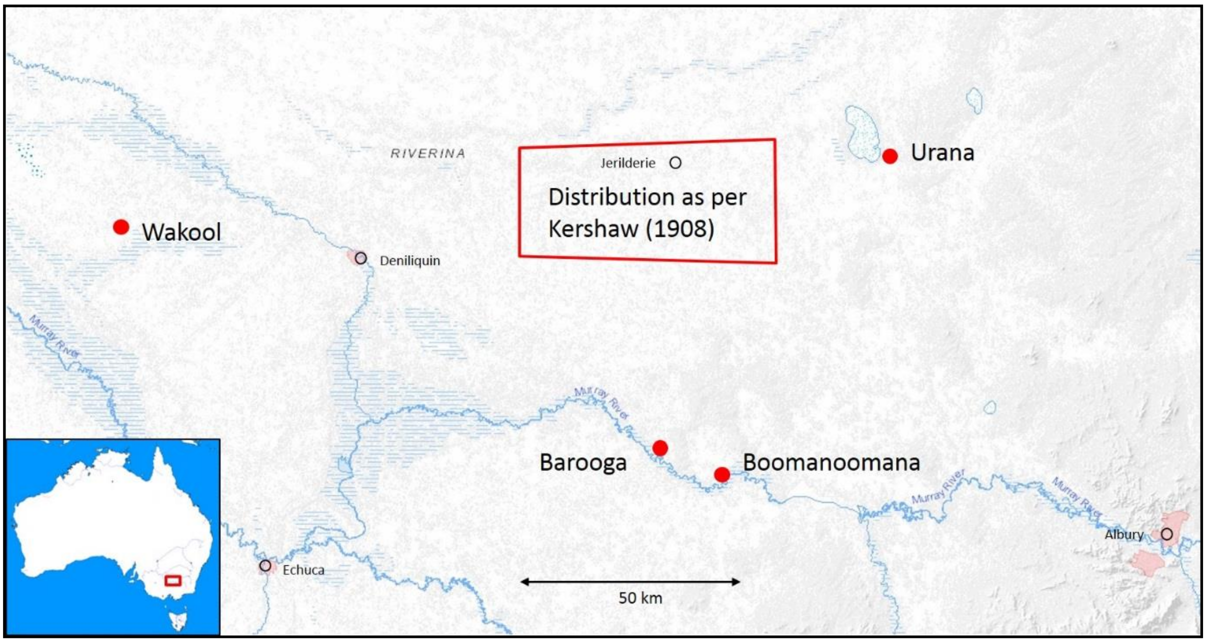


*Figure 7: Reported location of northern hairy-nosed wombats in the NSW Riverina.*

By the 1880s, concerted efforts were underway to remove wombats from the area (The Riverine Grazier 1883). A meeting of the Deniliquin Pastoral Board in 1884 declared wombats to be noxious animals and placed a 5s. bounty on each animal destroyed (South Australian Register 1884). This bounty was enthusiastically pursued, with over 1,000 wombats being destroyed on one property alone in just one year (The Australasian 1885). Although wombats did cause damage to farm properties, the main reason for their declaration as pests was only partly related to the damage caused by wombats themselves, which were described as harmless creatures which did little damage (The Australasian 1893). Rather, it was because wombat burrows provided a safe haven for rabbits, which had first appeared in the district in 1879 (The Australasian 1885). The rabbit problem was so bad that farmers were prosecuted and fined for not controlling rabbits on their properties; control which usually involved the destruction of wombat burrows to eliminate potential rabbit habitats (Tocumwal Guardian and Riverina Echo 1914). The destruction of wombats and their burrows was so effective that within 13 years sightings of wombats in the Riverina were rare (The Sydney Morning Herald 1897). Reports describe rabbits as infesting abandoned wombat burrows (Jerilderie Herald and Urana Advertiser 1907, 1913), and there are no mentions of wombats themselves. This suggests that they were either close to, or were locally extinct by the first decade of the twentieth century. Despite this, there have been some suggestions that a remnant population of hairy-nosed wombats may have survived in the area until at least 1985; along the Edward River in the Tuppal State Forest to the south-east of Deniliquin (Woodford 2001). Active burrows and fresh scats which possibly contained northern-hairy-nosed wombat hairs were found, although no confirmed sightings have ever been made of the animals themselves. A follow-on expedition in 2001 to locate wombats in the area failed to find any, and burrows that were reported to be active in 1985 appeared to have been abandoned. Further complicating this issue is the sighting of a colony of common wombats in the area in 2008 (Herring and MacGregor 2008). How they came to be in the area is unknown, and it is possible they are the descendants of animals which were deliberately released into the area.

No records could be found of hairy-nosed wombats in locations such as Balranald; in the area between the northern hairy-nosed wombat population in the Riverina and the southern hairy-nosed wombats 200 km to the north-west near Euston. Although rabbits invaded the Balranald area at the same time as they arrived in Jerilderie and caused similar problems, the discussions of rabbits in the Balranald area do not make any reference to them inhabiting wombat burrows (The Sydney Morning Herald 1890; Wagga Wagga Advertiser 1891). Most telling, the Balranald Pastoral Protection Board and meetings of landholders in the Balranald area do not discuss wombat control as a means of controlling rabbits (The Sydney Mail and New South Wales Advertiser 1890; The Riverine Grazier 1907), despite it being certain that they would have been aware of the success of such measures in Jerilderie (The Australasian 1893). This lack of reference to wombats near Balranald, together with the claims that the Riverina wombats inhabited a limited area (The Australasian 1885), strongly suggests they were absent from the Balranald area at the time of European settlement.

One possible explanation for this gap is the Murrumbidgee River, which flows into the Murray approximately 50 km east of Euston. Although the confluence of the Murrumbidgee and Murray Rivers is generally considered to be a semi-arid region today, at the time of European settlement in the nineteenth century the area was a large natural wetlands called the ‘Lowbidgee Floodplain’ which comprised over 300,000 ha of swamps, billabongs and floodplain vegetative communities. However, the construction of upstream dams and water extraction for agriculture during the twentieth century reduced water flows, dried out the area and desiccated over 75% of the natural lakes and floodplains (Kingsford and Thomas 2004). Since hairy-nosed wombats have a strong preference for burrow construction in dry soils and are averse to inhabiting wetlands (Aitken 1971), in the nineteenth century the Lowbidgee Floodplain would have represented a formidable natural barrier.

*Wellington Caves and central / northern NSW*

The fragmentation of the hairy-nosed wombat population is apparent in the isolation of the Riverina sub-population from the other groups of northern hairy-nosed wombats which would have existed in the nineteenth century. The distance between the NSW Riverina and the other most southerly population around St George Forest in southern Queensland was ~ 1,000 km; with a further 700 km to Epping Forest. There is ample evidence of wombats occurring between Queensland and the NSW Riverina, along the western slopes of the Great Dividing Range at locations such as Mudgee, Bathurst and Tamworth (The Sydney Morning Herald 1913, 1939; The Tamworth Daily Observer 1914), and as far west as the Weddin Mountains near Grenfell (The Bathurst Daily Argus 1909). However, it is almost certain that these were common wombats rather than hairy-nosed, as common wombats persist in many of these locations today, and the reports make no reference to them being different, as occurred in all other locations where hairy-nosed wombats were encountered (McIlroy 1995).

The only definitive evidence for the occurrence of hairy-nosed wombats in central New South Wales comes from fossilised remains collected from Wellington Caves (Owen 1872; Dawson 1985); ~ 60 km to the west of Mudgee. This indicates that the former distribution of hairy-nosed wombats in central New South Wales would have overlapped the current distribution of common wombats. This further suggests that either common and hairy-nosed wombats once co-existed in the region, that common wombats competitively displaced hairy-nosed wombats, or that climatic or other habitat changes no longer suited hairy-nosed wombats and the new conditions were preferred by common wombats.

*Southern Queensland*

The presence of common wombats in southern Queensland had been reported by numerous sources from the latter half of the nineteenth century onwards; especially in the Stanthorpe region, 200 km south-west of Brisbane (Queensland Times, Ipswich Herald and General Advertiser 1877). However, information on hairy-nosed wombats from the early days of the European settlement of Queensland is less well reported.

Perhaps the first report of hairy-nosed wombats in Queensland was by Major Sir Thomas Mitchell (1847). In a journal entry on 6 May 1946, Mitchell describes the red rock of the country as being 'hollowed out by some burrowing animal'. The location of this report was from near Mount Red Cap, ~ 140 km to the north of St George (Figure 8). Mitchell's report was followed up by Ludwig Leichhardt in 1847, who describes the burrow and traces of an unknown animal at two locations near where the town of Surat now stands (Clarke 1860) (Figure 8). In the first, on the 26 August 1847, Leichhardt described the burrow of an unknown animal 'the size of a beaver', and mentioned tracks that, 'resembled that of a child' (Clark 1860). This description is remarkably similar to that of the tracks made by southern hairy-nosed wombats: 'the impressions of their feet in the sand-tracks... bear a striking resemblance to those of the footprints of a young child' (Angas 1861). On 7 September 1847, Leichhardt wrote 'we saw again the burrows of the new animal in the red soil... and there were many holes close together' (Clark 1860).

These reports are significant, as they place wombats well outside what is currently accepted as being their likely range in the first half of the twentieth century. There is also ~ 80 km between Mitchell's sightings and Leichhardt's. This suggests that the distribution of northern hairy-nosed wombats in Queensland at the time of European settlement may have been more widespread than previously thought.

In addition to the early reports by explorers, wombats were reported by locals ~ 40 km to the east of St George as early 1861, despite there being scepticism shown in some quarters to the reports (Darling Downs Gazette 1905). As a result, the presence of hairy-nosed wombats in Queensland was not confirmed until 1900, from an examination of three specimens which had been obtained between 1891 - 1899 along the Moonie River (De Vis 1900). They were immediately recognised as being different to both the common wombats which inhabited the

Stanthorpe region and the southern hairy-nosed wombats of SA, and they were assigned the taxonomic nomenclature *Phascolomys gillespiei*.

The three specimens described by De Vis (1900) were reported to have come from just north of St George and from a few miles east of Thallon, 80 km further south (De Vis 1900; The Brisbane Courier 1933). If the sightings by Mitchell and Leichhardt formed part of the St George population group, the geographic extent would have extended at least 200 km N/S x 60 km E/W (Figure 8). Mitchell's and Leichhardt's journals also provide an insight into the likely abundance of wombats in the region. Although Mitchell started his 1846 journey from St George's Bridge (now St George) and travelled along the Balonne and Cogoon Rivers as far north as Mount Elliott before returning along the Maranoa River, he makes no mentions of wombats or burrows other than in the vicinity of Mount Red Cap (Mitchell 1847). Similarly, although Leichhardt traversed the region to the north of St George from east to west along the Balonne River and the country just to its north, his only two mentions of wombat burrows were in the vicinity of where Surat now stands (Clarke 1860). This suggests that while the geographic extent of the wombat population in the region may have been quite large, it may also have been very patchy, with scattered colonies located in areas of suitable soil or vegetation. This is supported by locals in the region, who suggest that wombat burrows were found in only a few locations (Darling Downs Gazette 1905).

While St George population is thought to have gone locally extinct by 1908 (Horsup 1998), an expedition in 1923 to capture a hairy-nosed wombat from Hollymount Station, 60 km to the east of St George, reported that they had sighted fresh signs of a wombat in the area (The Advertiser 1923). Although an extensive search was conducted no wombats were seen, although they discovered 'scores' of burrows and fresh tracks along a tunnelled ridge that 'ran for miles'. As a consequence, wombats were assessed as being almost, but not quite, extinct in the district (Western Mail 1923). Soon after, wombats were being described as 'impossible to find along the Moonie' (Sydney Mail 1933), suggesting that they may have gone locally extinct in the 1920s. Despite this, there have been some unconfirmed reports of wombats in locations such as Ula Ula, 25 km to the east of Warrie, and Moombah Station on the Moonie River, as late as the 1950s (Crossman 1988). However, land clearance in these areas in the 1950s destroyed any evidence of past wombat activity, so these reports cannot be verified.

The reason why wombats went extinct in the St George region is not clear. Rabbits appeared in the Moonie River region near St George around 1892 (The Telegraph 1893; Stodart *et al.* 1988). While their numbers steadily increased (The Queenslander 1899), because of effective management actions and less favourable environmental conditions they never reached the scale of the plagues which were being experienced in the southern states (The Brisbane Courier 1906, 1927; Western Star and Roma Advertiser 1918). As a consequence, rabbits are sometimes discounted as the main reason behind the decline of wombats in Queensland, with the blame being placed on competition from livestock, especially during periods of drought (Crossman *et al.* 1994). However, given that the wombat decline in the region appears to coincide with the arrival of rabbits, they should not be discounted as a factor.

*Central Queensland*

The last remaining colony of the critically endangered northern hairy-nosed wombat is in the Epping Forest National Park ~ 110 km north-west of Clermont in central Queensland (Fig. 8). Because so few animals remain – less than 200 at the most recent estimate in 2014 – a management plan was developed for their recovery (Horsup 2004) and any changes to their population dynamics are the subject of close scrutiny (White *et al.* 2014).

The first confirmed report of hairy-nosed wombats in the Epping Forest area was not made until 1937 (Morning Bulletin 1937); although locals claim they had been aware of the presence of wombats in the area since settlement in the 1860s (Crossman 1988). The population at the time of the first report was said to cover a small area of approximately 6 miles x 1 mile (10 km x 2 km) (Morning Bulletin 1937). There is no information on the distribution of wombats in the area at the time of European settlement. However, the population appears to have undergone a number of contractions during the first half of the twentieth century. Inspections of the area between 1974 – 1982 revealed traces of disused wombat burrows on Alinya Station (formerly known as Laglan Station in the 1930s) 5 km to the west of Epping Forest, and at ranges of up to ~ 2 km to the south, east and north-east of the extant wombat distribution (Gordon *et al.* 1985). Another colony was said to exist near the Sandy Camp waterhole, approximately 10 km west of the present colony (Crossman 1988). Local residents suggest that wombats disappeared from some of these areas at about the same time as hairy-nosed wombats were first revealed to the general public in the late 1930s, with further contractions occurring in the 1960s (Crossman 1988).

The most commonly accepted explanation for the declines in the Epping Forest population during the first half of the twentieth century is competition from cattle grazing, especially during periods of drought (Crossman 1988). Rabbits can be discounted as a major factor as they did not arrive in the Epping Forest area until after 1940, and even then they were in small numbers only (Stodart *et al.* 1988). However, it is possible they may have had an influence on the continuing decline in abundance in the second half of the century.

*Other Queensland locations*

In addition to the known St George and Epping Forest populations of northern hairy-nosed wombats, there have been a number of unconfirmed reports of wombats at several locations in-between these two areas, and one which is further to the north (Crossman 1988) (Figure 8). These include:

- Carnarvon National Park – several reports up to the 1930s.
- Injune – wombats trapped in rabbit netting around sheep paddocks up to 1927, and sighted in the area near Mt Hutton in the later 1920s.
- Tambo – details unknown (1917)
- Mt Douglas – wombat injured and taken to a vet (date unknown).

Whilst some caution should be exercised in regard to these reports, their locations indicate the possibility that the St George and Epping Forest populations should not be considered in isolation. Rather, both sites may merely represent the densest population regions of a large – but extremely patchy – population group. Another limitation of these reports is that they all date from the 1920s onwards and do not cover the early days of European settlement in Queensland. As a consequence, they would only represent the status of the population after it had been subjected to the influences of European settlement for some decades.

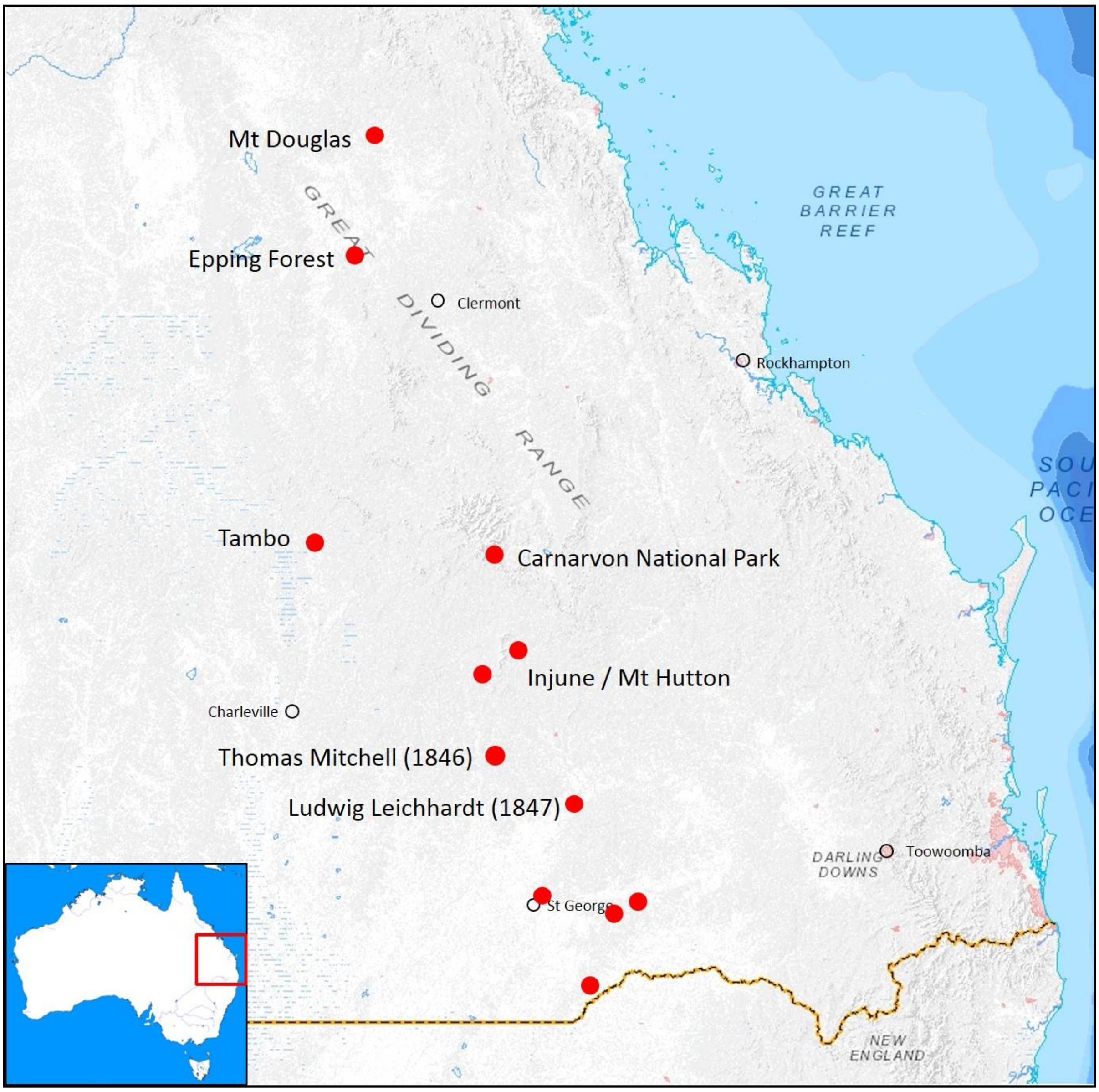


*Figure 8: Reported locations of northern hairy-nosed wombats in Queensland.*

**Conclusions and Recommendations for Further Research**

The overall distribution of southern hairy-nosed wombats at the time of European settlement was most likely split into two main groups on either side of Spencer Gulf in SA. The western group extended from Balladonia in WA to near Cowell on the western side of Spencer Gulf. A second main group of southern hairy-nosed wombats extended from the eastern side of Spencer Gulf; encompassing the Adelaide Plains and mid-north, Yorke Peninsula, Murraylands, and along the northern bank of the Murray River to Euston in NSW. The two isolated sub-population groups of wombats which currently exist in the Gawler Ranges were most likely already isolated at the time of European settlement by climate change and unfavourable soil and vegetation. (Figure 9).

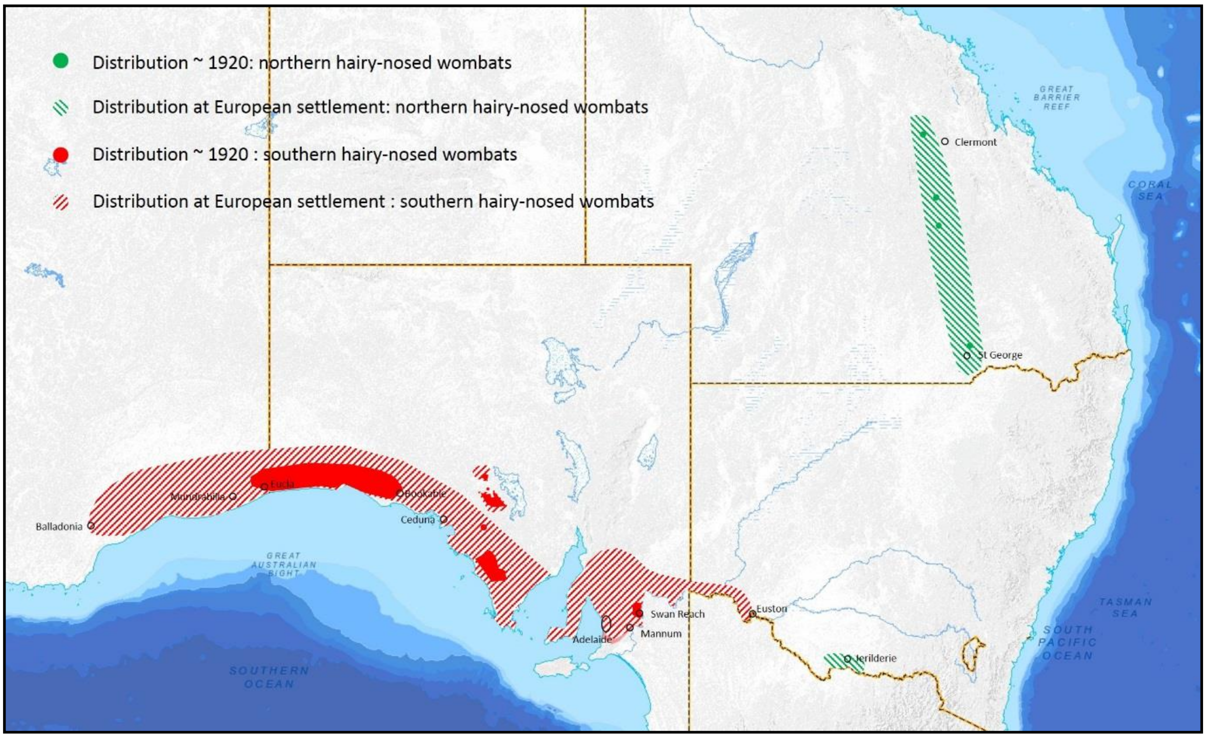


*Figure 9: Likely distribution of hairy-nosed wombats at the time of European settlement of Australia, and following major contractions from 1870 – 1920.*

Approximately 200 km further east of the eastern edge of the southern hairy-nosed population at Euston – separated by the Lowbidgee floodplain at the confluence of the Murrumbidgee and Murray Rivers – there was an abundant population of northern hairy-nosed wombats in the NSW Riverina centred around the town of Jerilderie. This group was separated from the only other populations of northern hairy-nosed wombats in southern and central Queensland by a gap of over 1,000 km. Although these wombats in Queensland are usually described as belonging to two distinct groups - Epping Forest and St George - it is probably more correct that the Queensland population should be thought of as one large – but highly patchy – group, with Epping Forest and St George the most densely populated areas (Figure 9).

The evidence suggests that all population groups of hairy-nosed wombats underwent significant range contractions following European settlement, with some groups going locally extinct. These contractions largely occurred between 1870 - 1920 (Figure 9), with some population groups experiencing a recovery in the latter half of the twentieth century. Whilst the distribution and abundance of southern hairy-nosed wombats have been assessed by a number of studies from 1970 onwards, there have been no surveys of some areas since the 1980s – especially the Gawler Ranges and Eyre Peninsula. More research is required to determine what changes may have occurred in these populations over the past 30 years.

There is a strong correlation between the arrival of rabbits in an area in the late nineteenth / early twentieth centuries and a decline in the wombat population, and with a recovery in wombat numbers following the biological control of rabbits (myxomatosis and RHDV) in the late twentieth century (Aitken 1971, 1973; Bird *et al.* 2012). This suggests that the biggest impacts on hairy-nosed wombats appear to be the presence of rabbits in large numbers, and the control actions undertaken in order to suppress both rabbits and wombats themselves (warren ripping and fumigating etc.). The other most important factors are land use changes for cropping agriculture and the expansion of human settlements. As a consequence, the continued control of rabbit numbers via means that do not adversely impact wombats is considered to be one of the most important factors influencing wombat conservation in the short to medium future. Continued management actions and further research are strongly recommended in this area.

Finally, comparisons of the distribution of hairy-nosed wombats at the time of European settlement to some of the known locations in the late Pleistocene / early Holocene suggests that the drying of the interior of the country and associated vegetation changes may have been unfavourable to wombats, and the distribution appears to have contracted towards the eastern and southern coasts. This suggests that the distribution of hairy-nosed wombats may be sensitive to climate change. Given the potential for more climatic changes to occur in the areas they currently inhabit and the limited capacity for further range shifts, more research is recommended in order to understand the threat that future climate change and other environmental factors might play on wombat distribution and abundance.

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to as coming from the Jerilderie area rather than Deniliquin, and he deserves the credit for the idea.

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# Statement of Authorship

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# Chapter 3: Using satellite imagery to assess the distribution and abundance of southern hairy-nosed wombats (*Lasiorhinus latifrons*)

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**Abstract**

*Monitoring of the southern hairy-nosed wombat (Lasiorhinus latifrons) population via satellite imagery was first proposed in 1980. However, the imagery that was available at that time was inadequate for the task as it did not permit the direct observation and counting of warrens. Since then, advances in the availability and resolution of satellite imagery mean that it is now possible to map the entire distribution of southern hairy-nosed wombats and to estimate their population abundance using very high-resolution imagery (≤ 1.0 m). However, other landscape features such as rabbit warrens can make the identification of wombat warrens problematic, and not all wombat warrens are visible, even in the best resolution imagery. By comparing data that we collected from field surveys conducted between May 2015 – May 2017 with satellite imagery we could identify that many wombat warrens have visible trails linking warrens with each other. Whilst this allowed us to differentiate between wombat and rabbit warrens in most circumstances, the lack of visible trails in some instances highlighted the need for ground truthing surveys to be conducted as part of any broad scale wombat population survey. Based on the difference between the number of warrens that we marked during our ground surveys with the number which were visible in the satellite imagery, we calculated a range of indices which can be used to correct future broad-scale population estimates based on satellite imagery, to account for warrens which may be obscured by vegetation and other confounding factors.*

## Introduction

The remote sensing of wildlife species using satellites has undergone significant development since their use was first mooted in the 1960s (NAS 1969; Buechner et al. 1971). Early uses were largely restricted to the collection of radio-tracking and telemetry data from tagged animals (Fancy et al. 1988). However, by the 1980s satellites were also being used to map potential wildlife habitat, which could then be correlated with populations of animals (Saxon 1983; De Wulf et al. 1988; Miller and Conroy 1990).

One of the first uses of satellites to observe animals and their effects on the ecosystem, rather than using telemetry data, was undertaken in the late 1970s (Löffler and Margules 1980). The study involved using Landsat imagery to map the warrens of southern hairy-nosed wombats (*Lasiorhinus latifrons*) on the Nullarbor Plains in South Australia by detecting the grazing damage that wombats caused (grazing 'halos') around large clusters of warrens. The southern hairy-nosed wombat was thought to be an ideal candidate species for satellite monitoring. They generally inhabit open landscapes with little to no canopy cover, so their warrens can be readily visible from above. However, the relatively poor resolution of the imagery which was available in the 1970s meant that even the largest warrens could not be directly detected. Consequently, unless grazing halos were present around warrens in all locations where wombats could be found – something which ground surveys showed was not the case (Tiver 1981) – the technique would have had only a limited application.

Southern hairy-nosed wombats are one of the largest burrowing species in the world, growing up to a metre in length and weighing up to 40 kg. They inhabit a fragmented distribution across the semi-arid regions of south-central South Australia and the south-eastern corner of Western Australia (Figure 1). Southern hairy-nosed wombats construct large warrens which can be up to one hectare in area and contain up to 70 burrow entrances (Taggart and Temple-Smith 2008), and each wombat uses multiple warrens within a relatively small home range (Finlayson et al. 2005; Walker et al. 2007). The burrowing and grazing habits of wombats can cause significant damage to agricultural land and infrastructure (Stott 1998), and dealing with their impacts is one of the major concerns expressed by farmers in regions where wombats are present (Sparrow et al. 2011; Taggart and Ostendorf 2012). These regions are also predicted to experience increased temperature and decreased rainfall due to anthropogenic climate change (Suppiah et al. 2006), and consequently southern hairy-nosed wombats are identified as a species at risk

(Marshall et al. 2017). Therefore, an accurate understanding of wombat distribution and abundance is essential for effective management of this species. Unfortunately, their fossorial and nocturnal nature makes studying wombats difficult, and estimating their abundance relies on a proxy measure of counting the number of burrows which are currently being used by wombats (active burrows) (Tiver 1980, 1981).

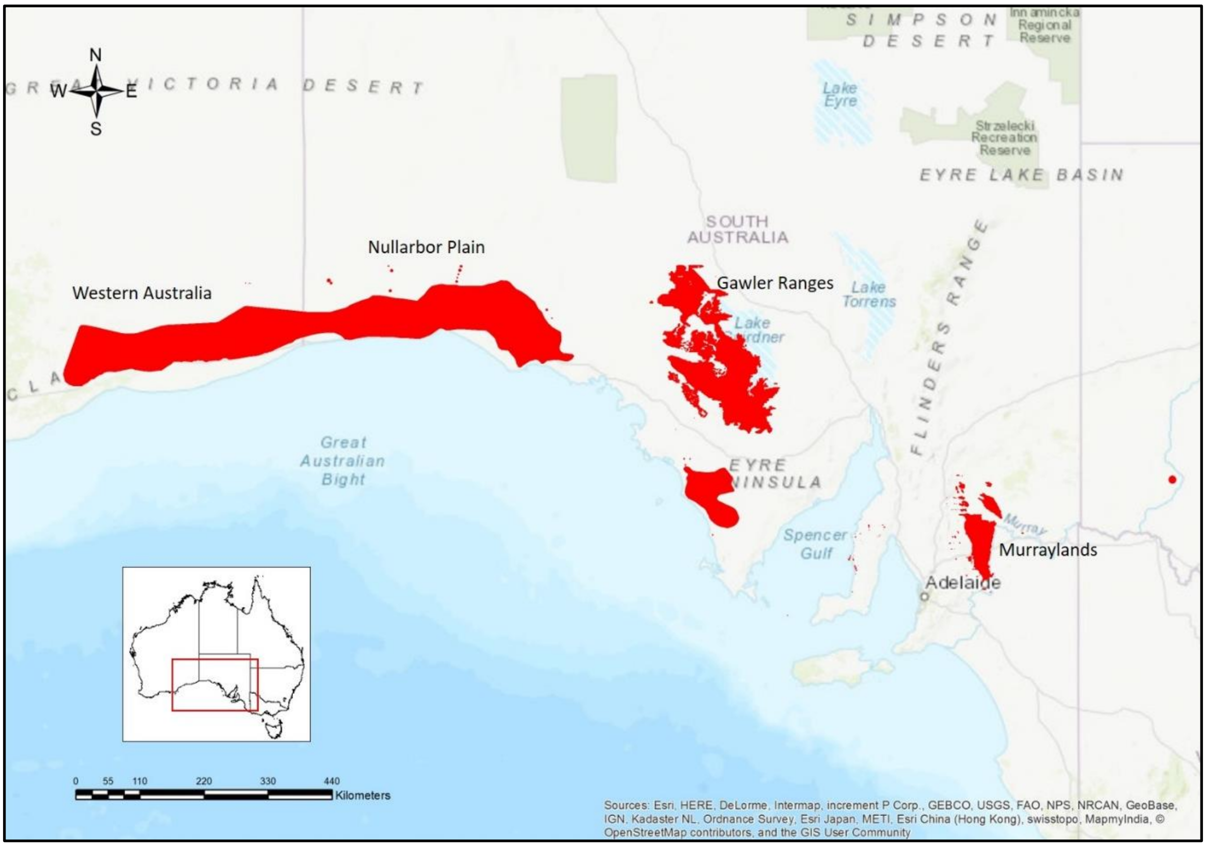


*Figure 1: Current distribution of southern hairy-nosed wombats. Using the techniques described in this paper, we have been able to update the extant distribution maps (Wells 2015), which have not been revised in some areas for over 30 years. In that time, the population in the Gawler Ranges region (centre of image) has expanded markedly, and we have mapped the full extent of the previously undescribed wombat population in Western Australia.*

Since the 1980s, the resolution and availability of satellite imagery has increased dramatically. Commercial organisations now offer world-wide coverage of up-to-date, high-resolution imagery (< 1.0 m) for sale, whilst on-line applications such as Google Earth and Bing Maps freely provide almost global-wide coverage of imagery which was collected within the last few weeks or months. Satellite imagery can now be used for a range of wildlife management applications, from monitoring populations of a fossorial species at a local scale (black-tailed prairie dogs, *Cynomys ludovicianus;* (Sidle et al. 2002)), to directly detecting individuals in a bird colony (albatross, *Diomedea* spp.; (Fretwell et al. 2017)). Given recent increases in technology and availability of imagery, it is now appropriate to revisit the potential for satellite imagery to be used as a tool to help monitor and manage the southern hairy-nosed wombat population.

**Method**

During field surveys conducted between May 2015 – May 2017 across three of the four main southern hairy-nosed wombat sub-populations in south eastern Western Australia and the Nullarbor Plains and Gawler Ranges of South Australia, we collected data on wombat warrens in each region (Figure 1). Warren positions were marked with a hand-held GPS (Garmin eTrex 10) and warren sizes were measured by pacing across the diagonal axis. The total number of burrows and the number of active burrows were also recorded. Burrows were assessed as active if there were signs of recent digging (within the past few days), wombat footprints, fresh scats, or visual or audible signs of a wombat in the burrow. Warrens were divided into four size classes based on their diameter: small (1 – 5 m); medium (> 5 – 15 m); large (> 15 - 35 m); and extra-large (> 35 m) (Tiver 1980, 1981; McGregor and Wells 1998; Taggart and Ostendorf 2012).

The warren data was converted to KML format and uploaded onto Google Earth Engine and the SAS.Planet (version 160707) satellite image and map viewing programs. The images were initially examined to determine any features of wombat warrens which would enable them to be positively identified from other landscape features such as rabbit warrens.

We examined the imagery to determine whether the warrens marked during the ground survey were visible, and compared the total number of warrens in each size class in the uploaded data with the number of these warrens which we could see in the highest resolution satellite imagery in both open grassland and scrubland. We defined scrubland as > 50% of the area surveyed being covered by low bushes (typically saltbush and/or bluebush) or tree canopies sufficient to obscure wombat warrens. Based on the difference between the number of warrens which were marked during the ground surveys versus the number which were visible in the imagery, we calculated indices for each warren size class in both open grassland and scrubland to be used to adjust broad-scale satellite surveys to correct for warrens which are not visible in the imagery (index = ground count ÷ satellite count).

We then measured the diameter of the warrens which were visible in the satellite imagery using the distance measurement tools in Google Earth and SAS.Planet and compared them to the measurements taken during the ground surveys.

Finally, one hundred and fifty of the marked warrens (50 from each of the three surveyed regions) were randomly selected and examined using the best available satellite imagery from four different sources (Landsat @ 30 m; Sentinel @ 10 m; Spot @ 2.5 m; and Worldview / Quickbird @ ~ 0.5 m) to determine the detectability of warrens of the different size classes.

All imagery analysis was undertaken by the lead author (MS), with a random selection cross-checked (AS) to compare and validate the results. All warren data from both the ground and satellite imagery analysis was collated in a Microsoft Excel spreadsheet (Microsoft Office Professional Plus 2013), and all statistical tests were performed using the Data Analysis add-in tools.

## Results

*Identifying wombat warrens*

The excavation of soil by wombats when constructing their warrens results in a heap of soil surrounding the burrow entrance, known as the 'spoil mound'. The soil in the spoil mound is often spectrally distinct to the surrounding area, and it is this contrast which makes warrens visible in satellite imagery. However, during our ground surveys we noted other landscape features such as exposed rock, mounds of stones collected by farmers, and the warrens of other fossorial species that also exhibited a similar contrast in the satellite imagery. We also noted that parts of the Nullarbor Plain are heavily infested with rabbit warrens (Figure 2).

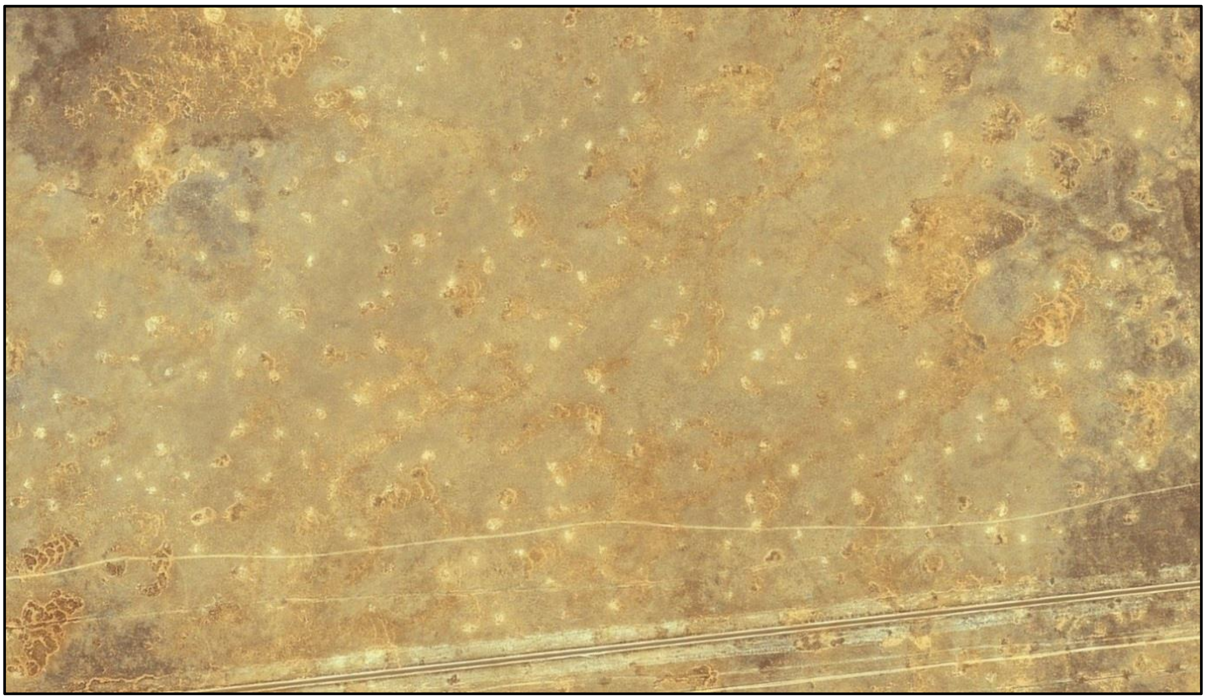

*Figure 2: Large number of European rabbit (Oryctolagus cuniculus) warrens (white dots) on the edge of the transcontinental railway line, 12 km to the east of the town of Forrest in Western Australia (30.834 S, 128.244 E). Differentiating between rabbit and wombat warrens is one of the major challenges when using satellite imagery to monitor the southern hairy-nosed wombat population, as they are spectrally similar and comparable in size.*

We noted that well-defined trails that radiate out from wombat warrens and provide links to other warrens within a colony could often be seen in the high-resolution satellite imagery (Figure 3). Similar trails were not observed between rabbit warrens; therefore, the presence of these inter-warren trails is a defining characteristic which enables positive identification of wombat warrens. However, we also noted that not all wombat warrens exhibit trails, and trails which appear similar can sometimes be evident in other landscape features such as around stock watering points (Figure 3). The difference that we observed between wombat trails and stock trails is that wombat trails either have both ends terminating at a warren, or are open ended trails leading from a warren for a short distance only, whereas stock trails tend to be longer and radiate out from a central point, usually a water or shelter point, with the other end extending into open country.

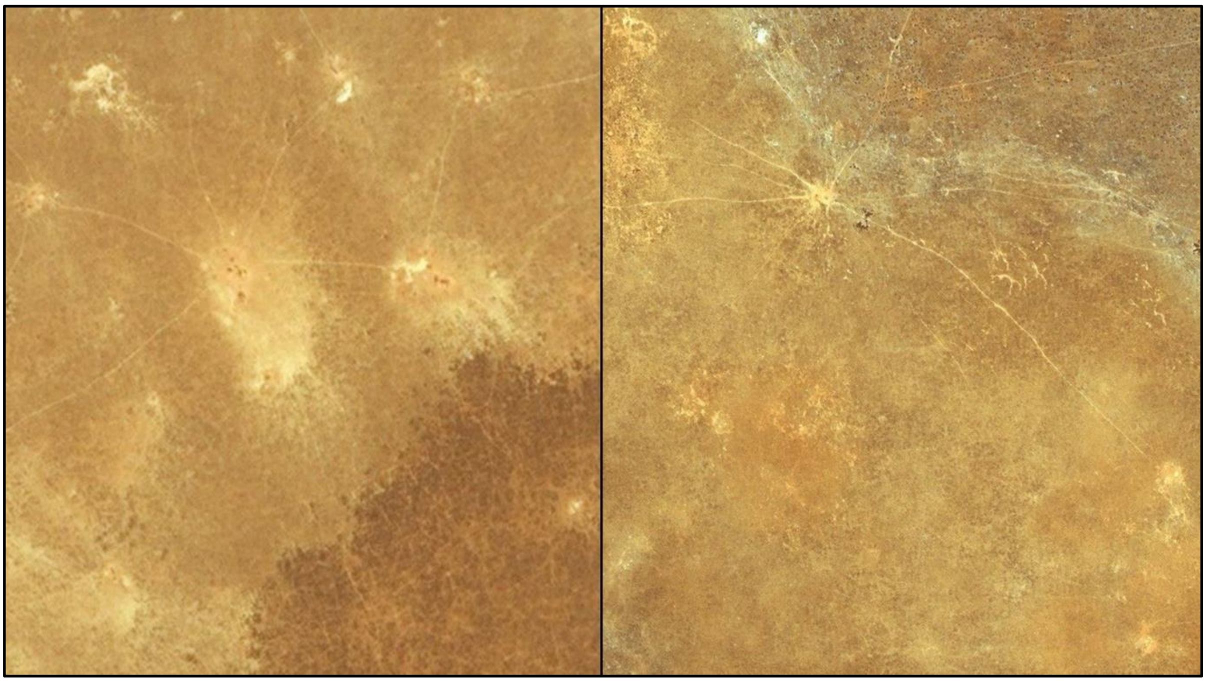

*Figure 3: Comparison between a colony of wombat warrens showing the characteristic interlinking trails between the warrens (left), and stock watering points with livestock trails (right). The similarity between such features can make the identification of wombat warrens difficult, and highlights the need for ground truthing surveys.*

*Satellite vs ground survey warren counts*

During our ground surveys we marked the position, and measured the attributes of, 1,204 warrens: Gawler Ranges - 597; Western Australia - 368; Nullarbor Plains - 239. The number of warrens in each size class were: small – 461 ($\hat{p}$ = 0.38); medium – 539 ($\hat{p}$ = 0.45); large -188 ($\hat{p}$ = 0.16); and extra-large – 16 ($\hat{p}$ = 0.01). Overall, 83% of all warrens marked during the ground surveys were ≤ 15 m in diameter (small – medium), with 38% being ≤ 5 m in diameter. Approximately 8 % of warrens were ≤ 2 m in diameter, and only 1% were > 35 m (extra-large) in diameter.

A comparison between the number of warrens that we marked during the ground surveys with the number that were visible in the satellite imagery showed that not all medium and small warrens could be detected, even at the highest resolution (< 1.0 m). Overall, all large and extra-large warrens that we marked were visible in the imagery, whereas 501/539 medium ($\hat{p}$ = 0.93) and 345/461 small warrens ($\hat{p}$ = 0.75) were visible. Warrens which had been constructed in scrubland were less likely to be visible in the imagery (40/64 small - $\hat{p}$ = 0.63; and 60/75 medium - $\hat{p}$ = 0.80) compared to warrens in open grassland (305/397 small - $\hat{p}$ = 0.77; and 441/464 medium - $\hat{p}$ = 0.95) (Table 1).

*Table 1: Comparison between the number of southern hairy-nosed wombat warrens marked during the ground surveys, vs the number of warrens which were visible in very-high resolution (< 1.0 m) satellite imagery. The 'Index' is the ratio between the ground count and the satellite count (Index = ground count ÷ satellite count), and can be used as a correction factor to adjust future satellite surveys to account for warrens which are not visible in the imagery.*

| Warren Size Class | Overall | | | Open Grassland | | | Scrubland | | |
|---|---|---|---|---|---|---|---|---|---|
| | Ground | Satellite | Index | Ground | Satellite | Index | Ground | Satellite | Index |
| **Small** | 461 | 345 | 1.34 | 397 | 305 | 1.30 | 64 | 40 | 1.60 |
| **Medium** | 539 | 501 | 1.08 | 464 | 441 | 1.05 | 75 | 60 | 1.25 |
| **Large** | 188 | 188 | 1.00 | 167 | 167 | 1.00 | 21 | 21 | 1.00 |
| **X-Large** | 16 | 16 | 1.00 | 14 | 14 | 1.00 | 2 | 2 | 1.00 |
| **Total** | 1,204 | 1,050 | | 1,042 | 927 | | 162 | 123 | |

We noted several reasons why warrens were not visible in the satellite imagery. These included (Figure 4):

- under vegetation;
- burrow entrance in a vertical surface such as a graded road edge or creek-bank;
- poor contrast between the spoil mound and the surrounding soil; and
- burrows were constructed under a ledge of calcrete, with no discernible spoil mound.


*Figure 4: Examples of southern hairy-nosed wombat warrens which are not visible in satellite imagery: (a) under vegetation; (b) constructed in a vertical surface (graded road edge); (c) poor contrast between the spoil mound and the surrounding soil; and (d) under a shelf of calcrete limestone with no spoil mound.*

*Ground survey warren data*

The mean number of active burrows per warren for each size class is shown at Table 2. There was no significant difference (single factor ANOVA) between the mean number of active burrows per warren in the different regions surveyed for small ($F$ = 2.849); large ($F$ = 1.102); and extra-large warrens ($F$ = 1.775). However, whilst there was no significant difference between the mean number of active burrows per medium warren in Western Australia and the Gawler Ranges (P = 0.064), there were fewer active burrows per medium warren in the Nullarbor Plains (P = 0.002); although this figure included 18 inactive warrens which had been abandoned following a flooding event. If these warrens are removed from the calculations, there is no significant difference in the revised figure (* in Table 2) of the mean number of active burrows per medium warren between all three regions.

*Table 2: Mean and SD of the number of active southern hairy-nosed wombat burrows within each warren size class for each of the surveyed regions. Starred (*) figures for medium-sized warrens are the mean and SD after removing 18 inactive warrens which had been abandoned following a flooding event.*

| | **Western Australia** | **Nullarbor Plains** | **Gawler Ranges** | **Overall** |
|---|---|---|---|---|
| **Small** | 0.84 (σ = 0.58) | 0.88 (σ = 0.46) | 0.98 (σ = 0.40) | 0.92 (σ = 0.60) |
| **Medium** | 1.77 (σ = 1.52) | 1.64 (σ = 1.14)<br>1.97 (σ = 0.98) * | 2.06 (σ = 1.58) | 1.88 (σ = 1.50)<br>2.00 (σ = 1.44) * |
| **Large** | 3.61 (σ = 2.45) | 4.59 (σ = 2.86) | 4.56 (σ = 3.17) | 4.45 (σ = 2.91) |
| **Extra-Large** | N/A | 6.64 (σ = 4.06) | 10.60 (σ = 3.20) | 7.88 (σ = 3.97) |

There was a significantly lower proportion of small warrens and significantly greater proportion of large warrens on the Nullarbor Plain than in either Western Australia or the Gawler Ranges (Figure 5). The proportion of active burrows to overall burrows was higher in the Gawler Ranges ($\hat{p}$ = 0.82) than in Western Australia ($\hat{p}$ = 0.73) and the Nullarbor Plain ($\hat{p}$ = 0.71).

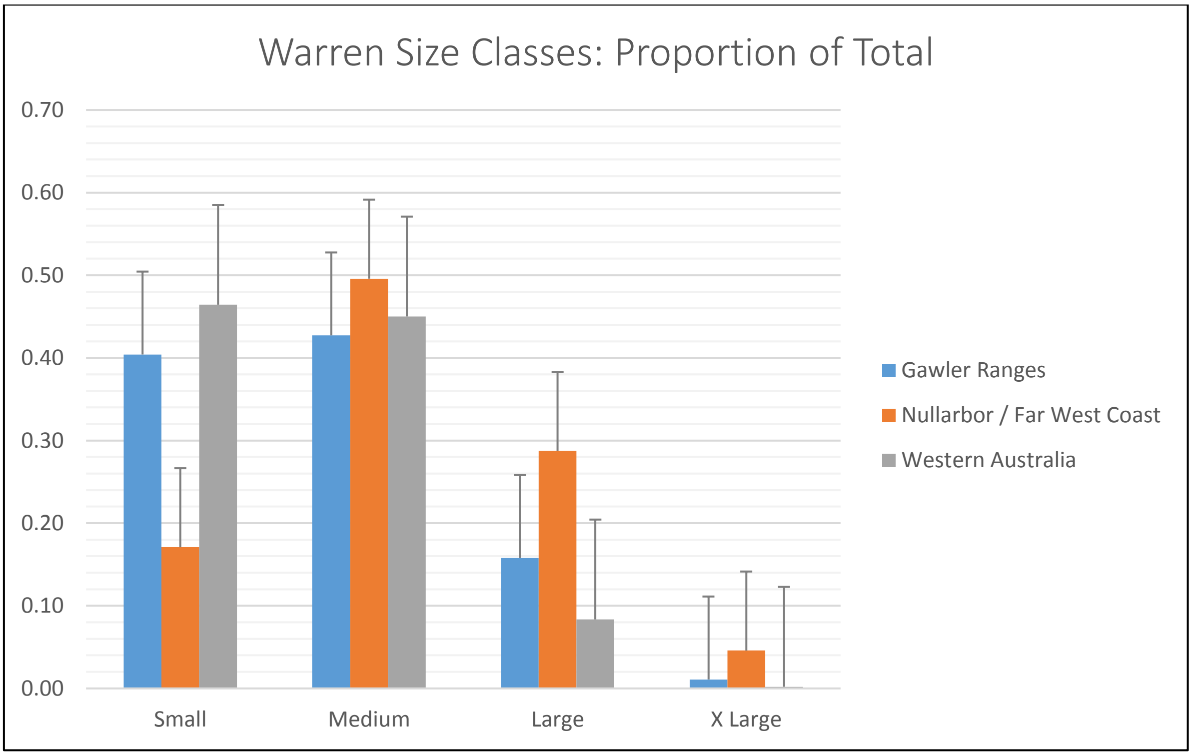


*Figure 5: Regional variations in the proportion of southern hairy-nosed wombat warrens of the different size classes.*

*Satellite vs ground survey warren measurements*

Pairing the measurements of the diameter of the warrens taken during the ground survey with the measurements of the same warrens visible in the satellite imagery provided 1,050 paired observations for comparative purposes. We found no significant difference between the overall mean of the ground measurements (10.23 m ($\sigma$ = 8.06)) and the satellite measurements (10.02 m ($\sigma$ = 7.84) (P = 0.549). However, a 't test: paired two sample for means' found a significant difference between the individual ground and satellite measurements, with the ground measurements being larger by 0.21 m (P = 1.86E $^{-7}$).

Because of this difference between the ground and satellite measurements, we assessed more warrens as 'small' and fewer as 'medium', 'large' and 'extra-large' in our analysis of the satellite imagery than we did during the ground surveys (Table 3). Conflating these differences in the proportions with the mean number of active burrows for each warren size class results in a calculated difference of ~ 2.2% in the total number of active burrows between the ground and satellite imagery analyses.

*Table 3: A comparison between the number of southern hairy-nosed wombat warrens of each size class that we counted during our analysis of the satellite imagery vs the same warrens measured during the ground surveys.*

| **Size Class** | **Small** | | **Medium** | | **Large** | | **Extra Large** | |
|---|---|---|---|---|---|---|---|---|
| | Count | $\hat{p}$ | Count | $\hat{p}$ | Count | $\hat{p}$ | Count | $\hat{p}$ |
| **Ground** | 345 | 0.33 | 501 | 0.48 | 188 | 0.18 | 16 | 0.01 |
| **Satellite** | 365 | 0.35 | 493 | 0.47 | 182 | 0.17 | 10 | 0.01 |

*Table 4: Number of southern hairy-nosed wombat warrens of the different size classes which were visible in satellite imagery of different resolutions, compared to the actual number of warrens which were marked during the ground surveys.*

| | **Small** | **Medium** | **Large** | **Extra-Large** |
|---|---|---|---|---|
| **Ground Count** | 57 | 69 | 21 | 3 |
| **Landsat (30 m)** | 0 | 0 | 0 | 2 |
| **Sentinel (10 m)** | 0 | 21 | 17 | 3 |
| **Spot (2.5 m)** | 42 | 65 | 21 | 3 |
| **WV/QB (0.5 m)** | 47 | 65 | 21 | 3 |

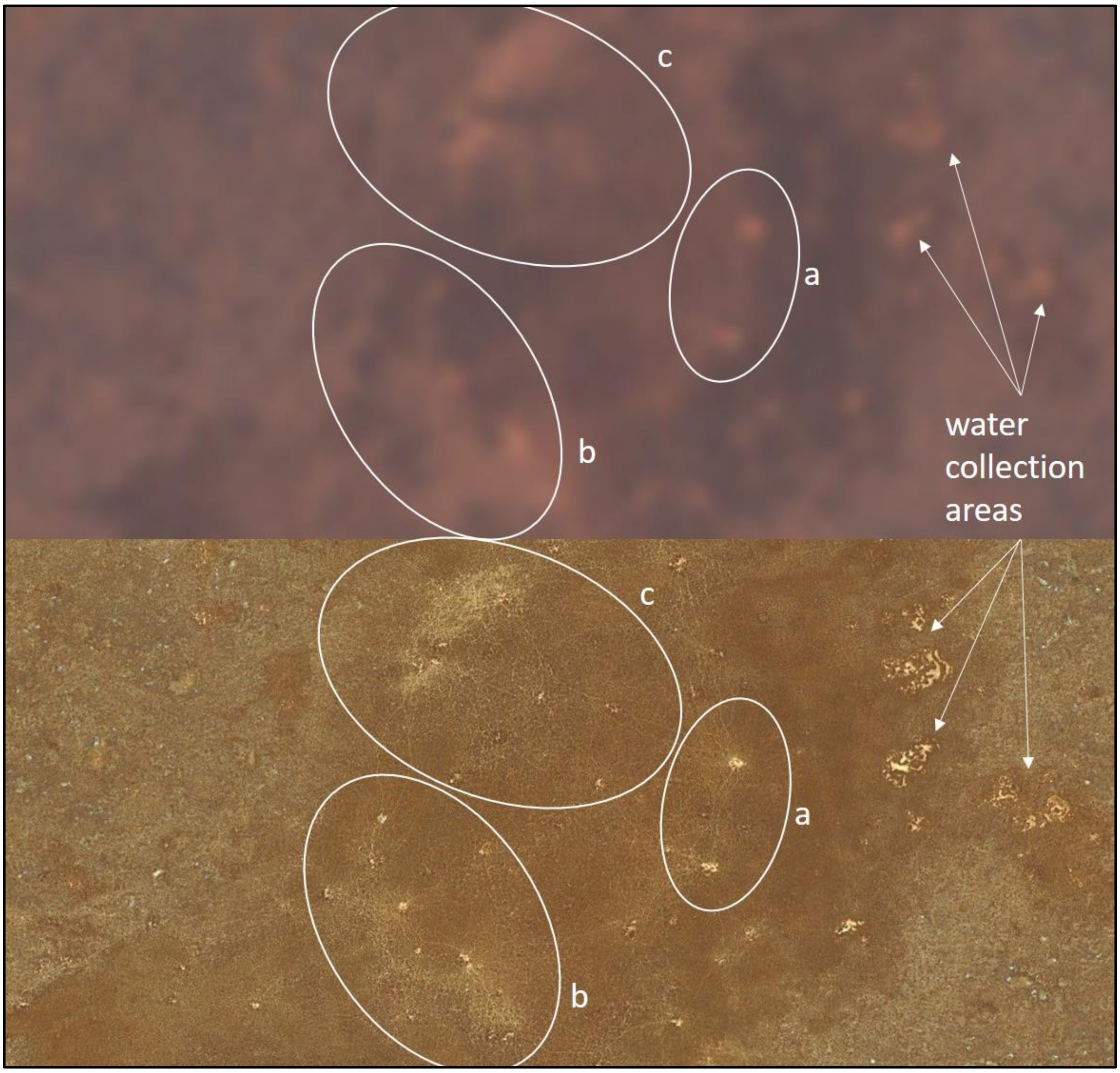


*Figure 6: Medium resolution Sentinel 2 (10 m) (top) and very-high resolution Worldview (<1.0 m) images taken of the same area to the north of Eucla in Western Australia (-31.432, 128.982), highlighting the differences in detectability, identification and ability to accurately measure the size of wombat warrens. Although the large warrens (area 'a') are visible in both images, discriminating between the warrens, grazing halos, and other landscape features such as low points where water collects is difficult in the medium resolution image, as they are spectrally similar and the characteristic inter-warren trails are not visible. Some of the medium warrens (area 'b') are visible but spatially indistinct in the Sentinel image, whilst the smaller warrens (area 'c') are not visible, especially when the spectral contrast between the warren and the background is low, such as when grazing halos are present (light area around the warrens).*

*Image resolution and warren visibility*

A comparison between the 150 randomly selected warrens that we marked during the ground surveys with the number of warrens which were visible in satellite imagery at the same locations at four different resolutions is shown at Table 4. In general, the number of warrens which were visible in the imagery increased as the resolution improved. In the lowest resolution imagery (Landsat 30 m), only extra-large warrens could be directly detected, whereas at 10 m resolution (Sentinel), medium warrens could be detected (21/69; $\hat{p}$ = 0.30), but not small warrens. Small warrens could only be detected at 2.5 m resolution (Spot; 42/57; $\hat{p}$ = 0.74) and at 0.5 m resolution (WV/QB; 47/57; $\hat{p}$ = 0.82) (Figure 6).

## Discussion

The first task in any assessment of the southern hairy-nosed wombat population based on satellite imagery is identifying which features on the imagery are warrens and which are not. In order to be directly detected in satellite imagery, the impact of the animals on the landscape needs to be spatially and spectrally distinct (Leyequien et al. 2007). Unfortunately, discriminating between wombat warrens and other landscape features such as rabbit warrens or areas of bare soil in satellite imagery can be difficult, as these features can be spectrally similar (McGregor 1992). This can result in a large number of 'false positives'; and whilst this issue has been previously recognised for spectral imagery analysis (Velasco 2009), it must also be considered for the panchromatic imagery analysis that we conducted.

Individual wombats do not normally live in a single warren, but are known to use several different warrens throughout their home range, and multiple wombats will use each warren (Finlayson et al. 2005). In moving between different warrens, the wombats create and follow well-defined trails, and these trails can make the identification of wombat warrens simple in some circumstances. Unfortunately, trails are not always present or visible, so their absence from satellite imagery does not preclude the possibility that the feature being observed is a wombat warren. Warrens can appear different in different regions due to a variety of factors such as land-use, soil type and depth, vegetation, season and topography. We found that by undertaking ground surveys of an area before analysing the satellite imagery, we could better understand the characteristics of warrens in the area. Mapping both wombat warrens and other 'non-wombat' features in an area such as rabbit warrens then gave us a high degree of confidence that we were correctly identifying features in the imagery that were wombat warrens and rejecting those that were not. Consequently, we would strongly recommend that ground-truthing surveys be undertaken prior to any wombat population monitoring activities based on satellite imagery.

Whilst low resolution imagery such as Landsat is not a useful tool to map wombat warrens, even very high-resolution imagery (< 1.0 m) does not necessarily reveal all the warrens which are in an area. For example, in sandy soil or low dunes with little vegetation, we found that the spoil mound soil is often the same colour as the surrounding landscape, and consequently the warren is difficult to detect in the imagery. Conversely, in areas high in calcrete limestone the spoil mound soil tends to be a lighter colour than its surrounds due to the high limestone content in the soil which is brought to the surface during burrow construction or maintenance, and these warren types tend to be more visible in the imagery. In areas of dense saltbush / bluebush scrubland (*Chenopod* spp.), not only are warrens sometimes obscured by vegetation, but the wombats appear to favour movement along roads and tracks (pers. observation), and it is common to find burrows which have been constructed in the vertical surface along the graded road edge. Similarly, in hilly country wombats often construct their warrens along ephemeral creek lines, and these warrens are difficult to detect due to both being constructed in a vertical surface (creek bank) and under the canopies of trees which grow along the creek edges. At the local scale, the number of warrens which might be obscured in this way varies depending upon local factors, and so specifying a range of indices which are applicable to all situations is not appropriate. However, at the broad scale these local factors are likely to balance out. Therefore, we suggest that the indices that we calculated to correct for warren visibility (Table 1) should be used for any satellite imagery-based assessment of wombat abundance at the broad scale, but not at the local scale.

Local factors are also likely to have played a role in the variations between the number of small and large warrens in the different regions. A geographic expansion in the distribution of a fossorial species such as wombats requires the construction of new burrows - which will necessarily be small at first - whereas population growth within fixed boundaries is more likely to result in existing warrens being enlarged, as it is energetically more efficient to expand existing warrens that to construct new ones (Reichman and Smith 1990). To this end, during our surveys of both the Western Australia and Gawler Ranges populations we noted that both population groups have experienced significant growth in both distribution and abundance over the past few decades, whereas the Nullarbor Plains group has experienced population growth within relatively stable geographic boundaries. As we found more small warrens in the Gawler Ranges and Western Australia and more large warrens in the Nullarbor, the difference in the population growth pathways is a likely explanation.

There is also a logical explanation for the regional differences in the number of active burrows per medium warren. Whilst we found fewer active burrows per medium warren on the Nullarbor Plains than we did in Western Australia and the Gawler Ranges, there was no significant difference between the total number of burrows per medium warren (active + inactive burrows) in the three regions. This means that there was a higher number of inactive burrows per warren on the Nullarbor. The reason for this difference is related to one area that we surveyed (31.3041 S, 130.492 E) that included 18 medium-sized warrens ($\hat{p} = 0.15$ of the medium warrens that we surveyed on the Nullarbor) that had been constructed on a floodway. These warrens had all been damaged by a recent flood event, and they had been abandoned by the wombats and contained no active burrows. If these warrens are removed from the data analysis, there is no significant difference in the revised calculations of the mean number of active burrows per medium warren between the different regions surveyed (Table 2 *).

We were unable to definitively determine the reason for the difference between the ground survey and the satellite imagery warren size measurements. Possible explanations include inaccuracies in the ground measurements; inaccuracies in the measurements taken using the satellite imagery due to image or screen resolution; differences in the diagonal axis used for measurement purposes; or differences in the interpretation of what constitutes the edge of the warren. However, given all these potential sources of error in both the ground and satellite measuring processes, we believe that the overall impact of the mean difference between the two measurements (0.21 m) on any population survey (2.2% difference between the calculated number of active burrows) is probably as good as could be reasonably expected. Nevertheless, including this figure as a correction factor should be considered for satellite imagery based broad-scale surveys to account for potential measurement errors.

Finally, during our field surveys we noted numerous relict warren mounds that, based on the recovery of skeletal remains – especially lower jaw-bones - from within the mounds, were most likely constructed by burrowing bettongs (*Bettongia lesueur*). These mounds were most prevalent in the northern section of Gawler Ranges region. We could also clearly see these relict warrens in the very-high resolution imagery, which suggests that they may be a good candidate species for similar research using satellite imagery. Burrowing bettongs were once widespread across Australia (Woinarski et al. 2015), but competition with rabbits and human persecution have resulted in their extinction in the wild on mainland Australia since the 1960s (Short and Turner 1993). In order to determine the impacts of the decline of bettongs and other fossorial species on ecosystem function (Fleming et al. 2014) and to support reintroduction programs, a number of field studies have been conducted to map the distribution of relict warrens at contrasting scales and to understand their influence on landscape patch dynamics (Noble et al. 2007). Although this study focussed on satellite imagery analysis of southern hairy-nosed wombat warrens, the techniques discussed are likely to be applicable to other species such as the burrowing bettong or bilby (*Macrotis lagotis*) (Abbott 2001). As fossorial species such as these provide an important habitat niche for burrowing and non-burrowing species alike, to avoid predators and environmental extremes, and to help conserve energy and water in otherwise harsh environments (Ostendorf et al. 2016; Thornett et al. 2017), we recommend that consideration be given to undertaking similar research into mapping the distribution and abundance of other burrowing species using satellite imagery and the techniques discussed in this paper,

.

**Summary and Conclusion**

This paper provides a unique case study that demonstrates that it is possible to use satellite imagery to directly detect the burrows of a fossorial species and hence, the direct influence of the animals on the landscape. But it also highlights some of the limitations of using remote sensing for research of this nature.

Improvements in the geographic extent, availability and resolution of satellite imagery over the past 40 years means that constructing distribution models and estimating the population abundance of a fossorial species like the southern hairy-nosed wombat using satellite imagery is now a viable proposition. However, detecting and positively identifying the warrens of the target species (i.e. wombats) from other landscape features such as bare ground or the warrens of a non-target species (e.g. rabbits) still requires significant image interpretation. We would therefore strongly recommend that ground truthing surveys be conducted as part of any broad scale population analysis based on satellite imagery, to map warrens in the region and to identify any local features inherent in the warrens so they can be correlated with what is being observed in the imagery.

Whilst very-high resolution imagery is essential to map, accurately count and measure the size of wombat warrens, even the best resolution imagery will not reveal all the warrens in an area. Consequently, any abundance estimate made from satellite imagery needs to be adjusted to correct for a range of confounding factors, such as warrens which are hidden by vegetation. The indices that we provided in Table 1 should be used in future broad-scale surveys of the southern hairy-nosed wombat population to adjust the warren counts obtained from an analysis of the satellite imagery to correct for warrens which may not be visible.

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# Statement of Authorship

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| Contribution to the Paper | Identification of research gap, conceptualisation, study design, research and data collection, analysis, drafting of manuscript, submission and revision | | |
| Overall percentage (%) | 80% | | |
| Certification: | This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper. | | |
| Signature | | Date | 7 November 2018 |

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By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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# Chapter 4: Southern hairy-nosed wombats (*Lasiorhinus latifrons*) in the Gawler Ranges region of South Australia: population growth from 1988 – 2016

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**Abstract**

*The southern hairy-nosed wombat (Lasiorhinus latifrons) is the faunal emblem of South Australia. It is also considered to be an agricultural pest, as its burrowing activities can cause significant damage to agricultural land and infrastructure. Unfortunately, much of our knowledge of this species' population dynamics is limited and / or out of date. The aim of this study was to estimate the distribution and abundance of southern hairy-nosed wombats in the Gawler Ranges region of South Australia, and to identify any changes since the last survey in 1988. Using a combination of satellite imagery and a ground survey conducted in May 2016, we mapped the distribution of wombat warrens in the region and counted and measured all warrens within 1,000 randomly selected one square kilometre cells. We estimate the current wombat population in the Gawler Ranges to be 240,095 (149,051 – 311,595); an increase from 14,373 in 1988. This population growth is most likely linked to a long-term decline in the European rabbit population following the release of RHVD in the 1990s. In 2016 the IUCN upgraded the conservation status of southern hairy-nosed wombats from 'Least Concern' to 'Near Threatened' based on localised studies in the Murraylands, South Australia. Our findings suggest that this may not have been warranted.*

**Introduction**

The southern hairy-nosed wombat (*Lasiorhinus latifrons*) is a nocturnal and fossorial marsupial native to Australia. The species distribution is fragmented into five main regions and several small outlying colonies, located across the southern part of semi-arid, mainland Australia (St.John 1998; Taggart and Temple-Smith 2008) (Figure 1). Whilst southern hairy-nosed wombats are the faunal emblem of South Australia and are an iconic species nationally (Curtis 2014), they are also considered a pest species by many landholders as their burrowing habits can damage crops and farm infrastructure (Stott 1998). Consequently, ad-hoc management actions to both protect and to control wombats are being undertaken simultaneously by different sections of the community.

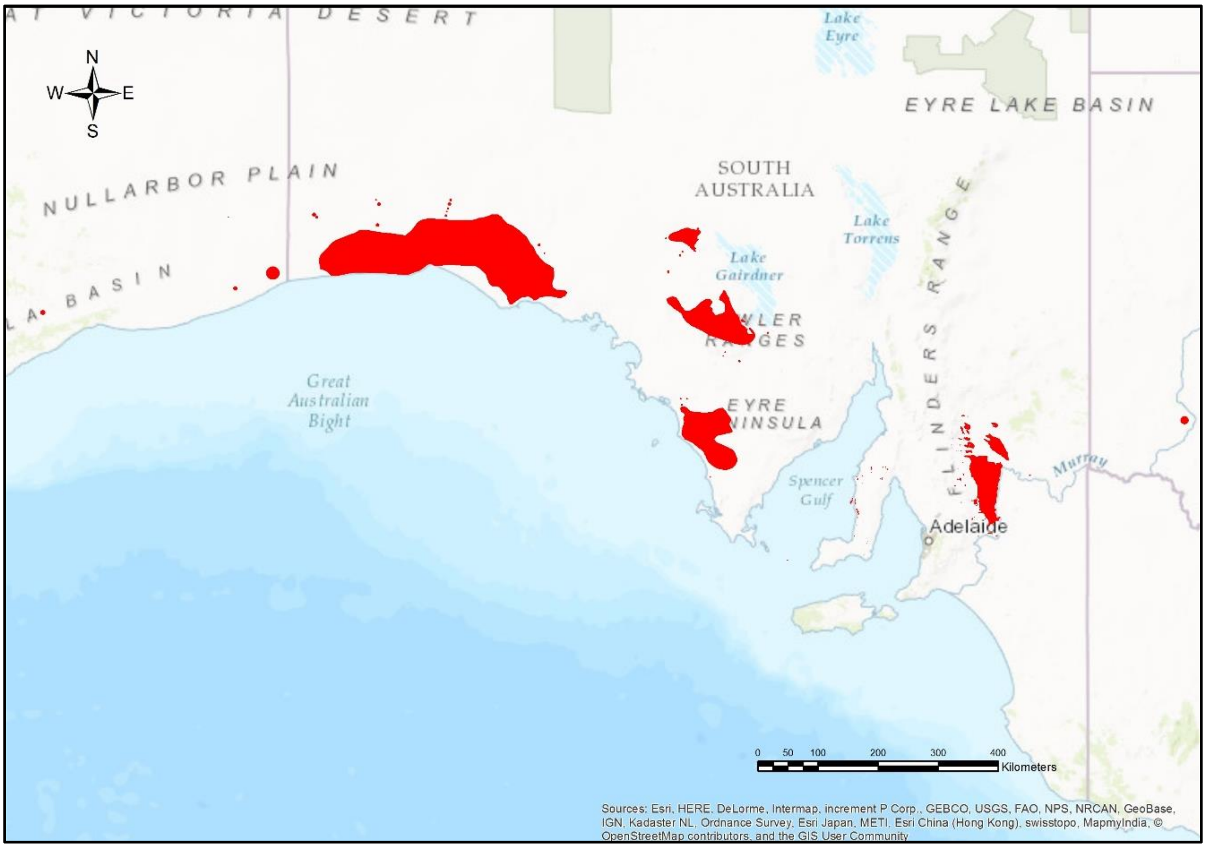


*Figure 1: Distribution of southern hairy-nosed wombats, showing the most recent survey data in each region: Murraylands (2012); Yorke Peninsula (2009); Eyre Peninsula (1988); Nullarbor and Far West Coast (2002); Western Australia (unsurveyed); and Gawler Ranges (1988).*

In its most recent published assessment in 2016, the International Union for Conservation of Nature (IUCN) upgraded the status of *L. latifrons* from ‘Least Concern’ to ‘Near Threatened’ (Woinarski and Burbidge 2016). In making this assessment, the IUCN suggested that the species almost qualified for a ‘Threatened’ listing, based on a ~ 70% decline in the population in the Murraylands region between 2002 – 2008 (Taggart and Temple-Smith 2008) following major droughts in 2002 and 2006-2008, leading to an overall population decline for the species approaching 30% over three generations. However, the IUCN also noted that the information on overall population abundance and trends was limited, and that many areas of the distribution had not been surveyed for over 20 years (Figure 1). In contrast to the IUCN assessment, landholders in, or adjacent to, most regions where *L. latifrons* are located, consistently claim that the wombat population has been increasing over the past few decades, and that they are now being found in areas where they have not been observed in living memory (Sparrow *et al.* 2011). Because of this disagreement over whether the overall population of wombats is increasing or decreasing, all stakeholders agree that better information is required to guide management decisions. However, estimating wombat numbers at the broad scale is difficult due to their cryptic nature and nocturnal and fossorial lifestyle (Taggart and Temple-Smith 2008), with animals using multiple burrows and warrens, and activity varying significantly between seasons (Finlayson *et al.* 2005).

One region where the information on the distribution and abundance of *L. latifrons* is sparse and out of date is the Gawler Ranges, ~ 200 km to the north-west of Port Augusta in South Australia (Figure 2). The Gawler Ranges region is highly heterogeneous in both landscape attributes and climate, encompassing areas dominated by claypans to the south (Locke Claypans); granite ridges which form the Gawler Ranges themselves; a band of vegetated sand dunes across the centre of the region, and a series of flat, ephemeral drainage areas to the west of Lake Harris and Lake Gairdner. Rainfall varies from ~ 335 mm/ annum in the south of the region, to around half that in the north (BoM 2016).

Only two broad-scale surveys of wombats in the region have been undertaken, the first in 1971 (Aitken 1971) and the second in 1985/88 (St.John and Saunders 1989). Two main sub-populations were identified – a small population to the west of Lake Harris, and a larger population centred to the south and west of Lake Acraman (Figure 2). Both surveys suggested that the Lake Acraman population had been undergoing a steady increase in distribution and abundance since the 1960s, and in 1988 numbered ~ 12,740 animals in an area of 3,787 $km^2$. However, the Lake Harris population was considered highly fragile and had not expanded between the two surveys, numbering only ~ 1,633 animals in an area of 536 $km^2$ (St.John 1998).

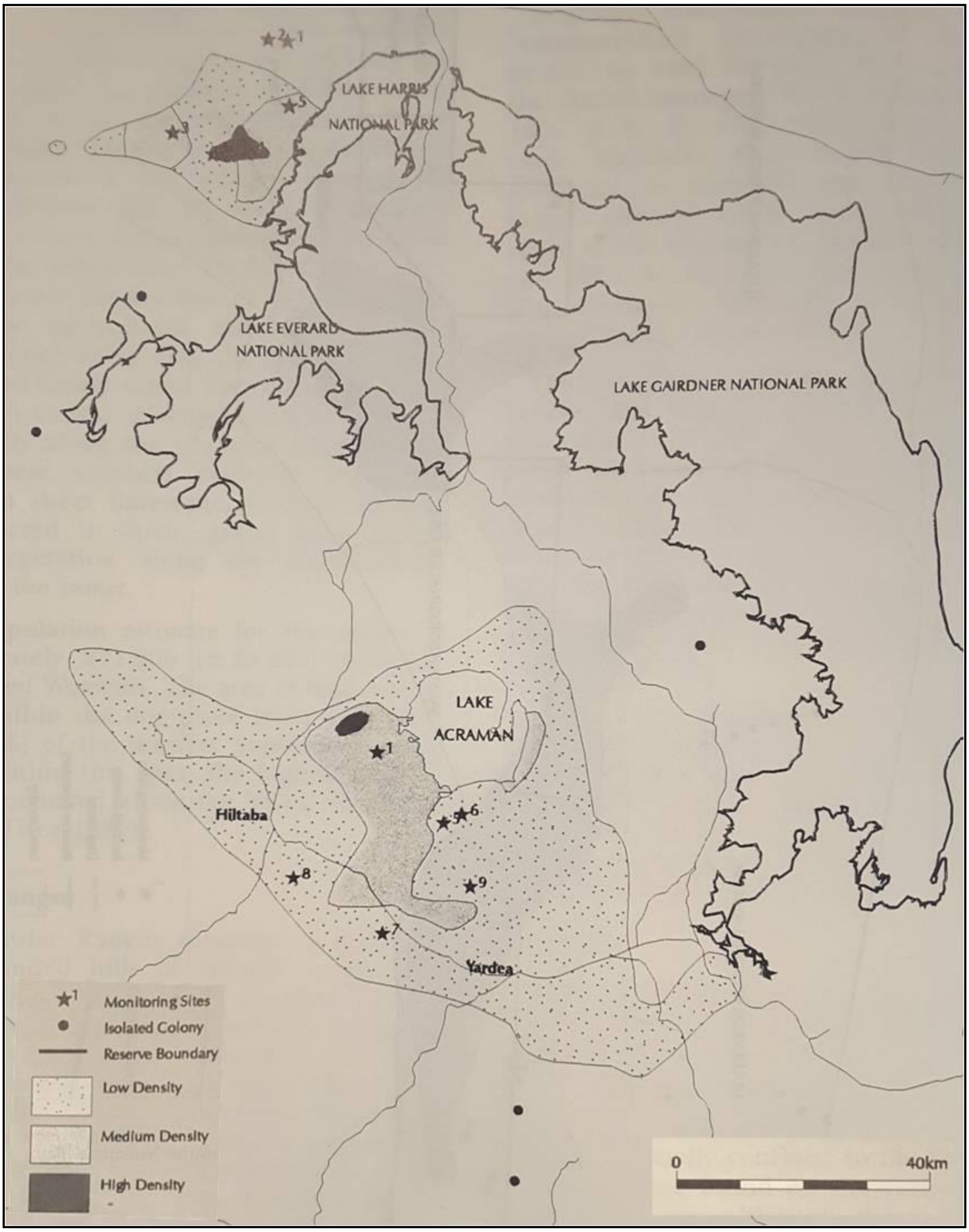


*Figure 2: Distribution of southern hairy-nosed wombats in the Gawler Ranges in 1988 (from St John 1998)*

Since the last survey in 1988 a number of large pastoral properties in the region have discontinued livestock grazing and converted to wildlife conservation (Blake 2016; Nankivell 2016), and a major competitor of wombats, the introduced European rabbit (*Oryctolagus* *cuniculus*) (Cooke 1998), has declined in numbers following the release of the rabbit haemorrhagic disease virus (RHDV) (Mutze *et al.* 1998). These changes are likely to have affected the distribution and abundance of wombats in the region (Pedler *et al.* 2016), and given the length of time since wombats were last surveyed (28 years), there is a clear need for an update.

## Method

### *Warren counts and classing*

Between 19 - 26 July 2016 we conducted a ground survey of the area by walking 102 transects to mark the position and measure the size of warrens, as well as to count the number of active and inactive burrows in each warren. Each transect was one kilometre long, and warrens within 50 m of the transect centre-line were marked and measured. At each site selected for the ground survey, transects were walked in groups of two on either side of, and perpendicular to, the road, with the second transect in each group offset from the first by ~ 300 m. Warren positions were marked with a hand-held GPS (Garmin eTrex 10) and warren sizes were estimated by pacing across the diagonal axis. Burrows were assessed as active if there were signs of recent digging (within the past few days), wombat footprints, fresh scats, or visual or audible signs of a wombat in the burrow. The positions of some warrens were also marked on an ad-hoc basis whilst driving between transect locations.

Measured warrens were separated into four size classes: small (0 – 5 m); medium (6 – 15m); large (16 - 35 m); and very large (> 35 m) (Tiver 1980; Tiver 1981; McGregor and Wells 1998; St.John 1998; Taggart *et al.* 2012).

### *Warren surveys using satellite imagery*

Wombat warrens can be visible on satellite images (Löffler and Margules 1980). In this study we used very high-resolution (better than 1.0 m resolution) satellite imagery that was collected between May 2014 – July 2016 and freely available on Google Earth and Bing Maps. Using ArcMap version 10.3.1, we overlaid a 300 x 200 km grid oriented north-south over the satellite imagery of the Gawler Ranges region (between 30.30 S – 33.00 S, 134.34 E – 136.36 E), with each grid square = one square kilometre. Lines of cells oriented north-south and east-west at five kilometre intervals were selected from the grid and inspected for the presence of wombat warrens. The cells containing wombat warrens which were closest to the edge of the grid were identified and used to construct an outline of the wombat distribution in the region.

Using the ArcMap Sampling Design tool, we randomly selected 1,000 grid cells (from a total of 19,077 cells within the outline distribution) for further analysis (5.24%, confidence level = 95%, margin of error = 3%). For each selected cell the date of the imagery was recorded, the presence or absence of warrens was noted, all warrens were counted, and their diameter measured.

Warren counts from the ground transects were compared with the counts of the same transects from satellite imagery, and indices were calculated to adjust the satellite counts to correct for additional warrens which may not be visible in the imagery (e.g. under vegetation). Indices were calculated for warrens of the four different size classes in both open grasslands and closed scrublands.

$$\text{Index} = \text{Ground Transect Count}_{\text{warren size class}} / \text{Satellite Count}_{\text{warren size class}}$$

The raw warren counts from the satellite imagery were adjusted using the calculated indices, and the adjusted warren counts were then multiplied by the mean number of active burrows for each warren size class, to provide a total number of active burrows for each grid cell. The active burrow data from all 1,000 randomly selected grid cells was then extrapolated by the total number of grid cells in the outline distribution (19,077) to provide an overall figure of the number of active burrows for the region.

$$\text{Grid Cell}_{\text{active burrows}} = \sum (\text{warren size class x Index x mean \# active burrows/size class})$$

$$\text{Active Burrows}_{\text{random cells}} = \sum^{1,000} \text{Grid Cell}_{\text{active burrows}}$$

$$\text{Active Burrows}_{\text{total}} = \text{Active Burrows}_{\text{random cells}} \text{ x } (19,077/1,000)$$

*Wombat abundance*

To calculate total wombat abundance (Wombats $_{\text{total}}$), we multiplied the total number of active burrows (Active Burrows $_{\text{total}}$) by indices of 0.32 (Taggart *et al.* 2012), 0.5 (St.John 1998) and

0.63 (Tiver 1980) wombats/active burrow to provide an estimated minimum, median and maximum number of wombats for the region.

$$Wombats_{total} = Active\ burrows_{total}\ (0.32, 0.5, 0.63)$$

**Results**

*Population distribution*

The distribution of wombats in the Gawler Ranges has expanded since 1988, and now encompasses an area of ~ 19,000 $km^2$ (Figure 3). However, landscape heterogeneity, especially the granite ridges of the Gawler Ranges themselves, areas of dense scrubby vegetation (e.g north of the Lockes Claypans) and the hard gibber plains to the north and east of Lake Harris means that much of this area not suitable for warren construction, with 51% (510/1,000) of our random grid squares containing no warrens (Figure 4). Approximately 92 % of the wombat distribution is encompassed within agricultural land (predominately sheep grazing), with the remainder in protected areas (Gawler Ranges National Park, Yellabinna Regional Reserve, Bon Bon Station and Hiltaba Station).

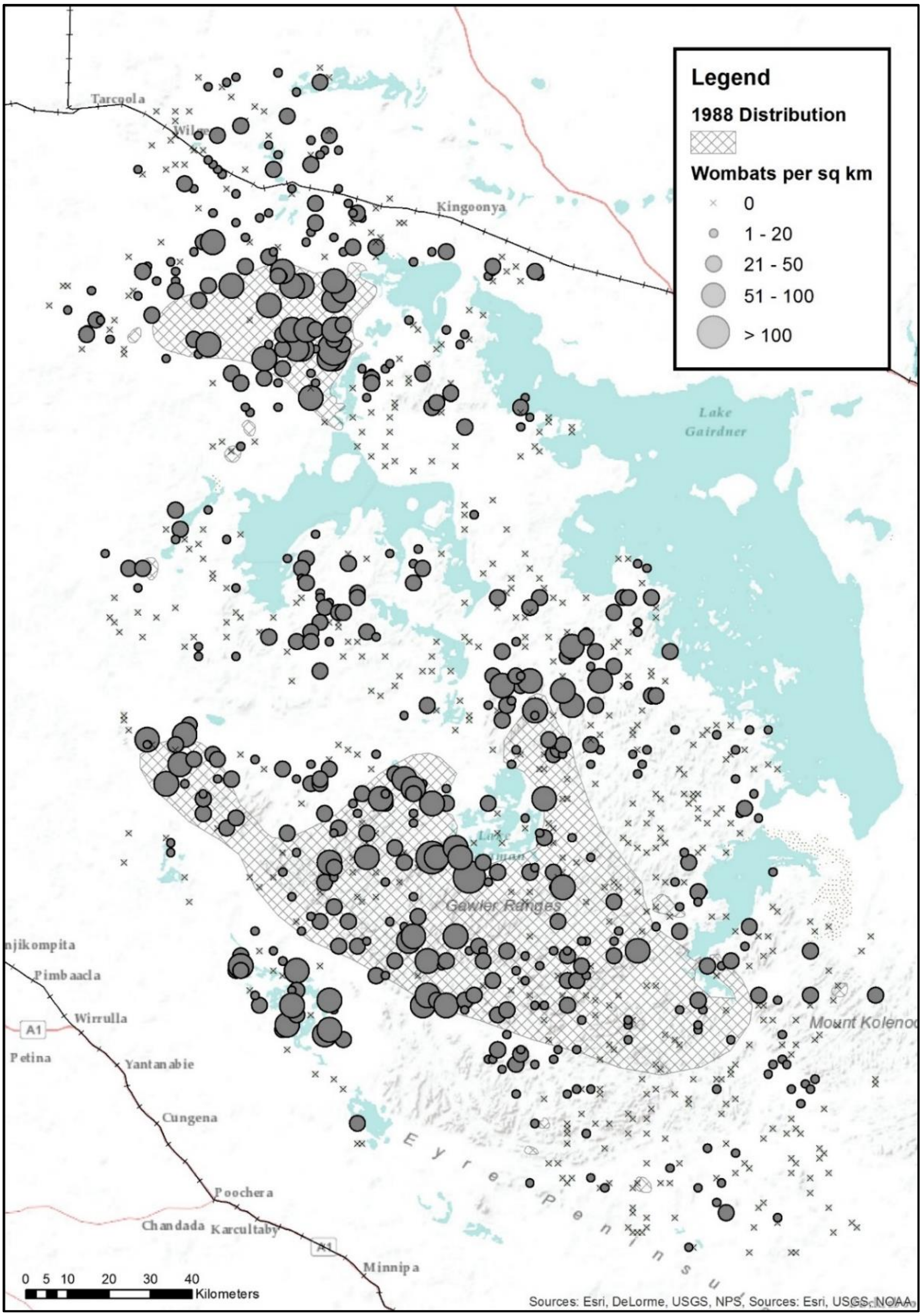


*Figure 3: Distribution and local area abundance of wombats in the Gawler Ranges. The points on this map are the 1,000 random grid squares used for analysis purposes. Note how the population density is highly variable. The landscape is highly heterogeneous, particularly in the southern half of the region around the ranges.*

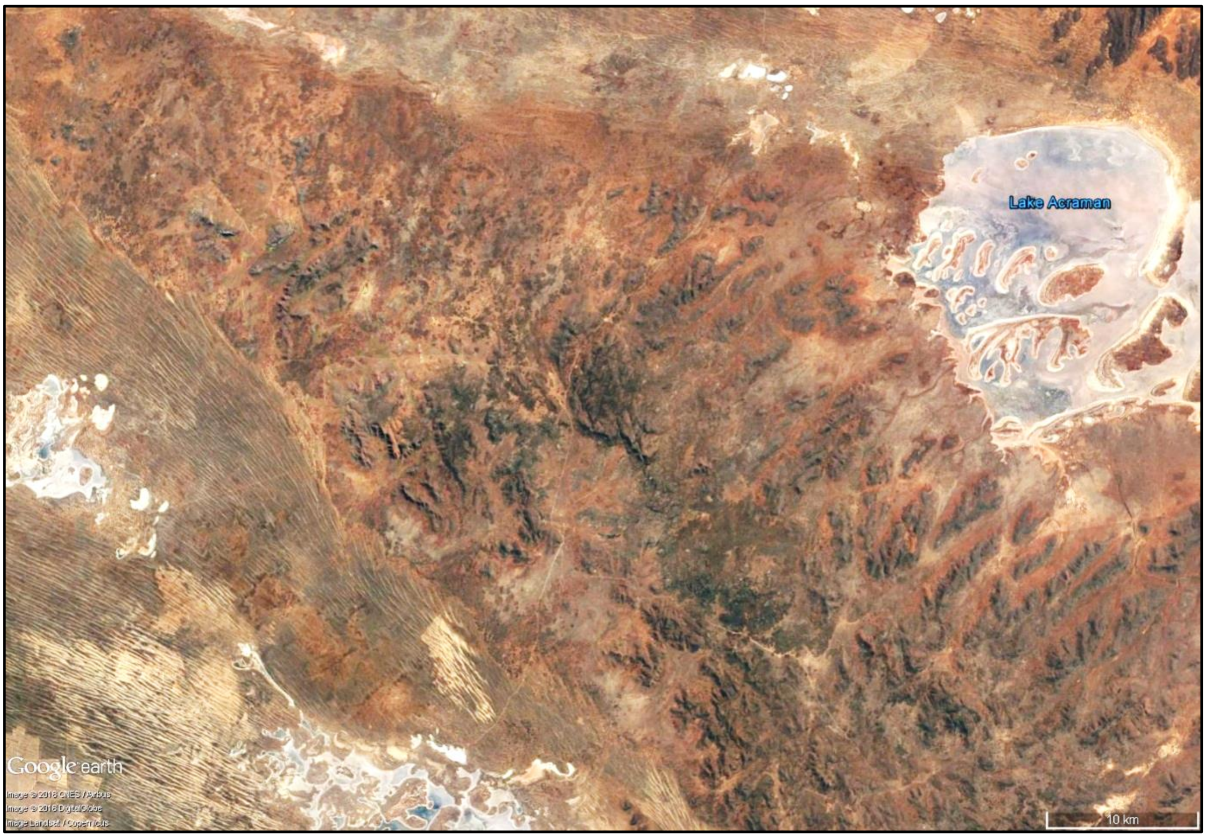


*Figure 4: Satellite image (Google Earth) of the area to the south-west of Lake Acraman, showing the landscape heterogeneity of the region. This image encompasses the lower third of Figure 3, and shows the landscape inhabited by the 'Lake Acraman' sub-population group. The dark areas in centre of the image are the granite ridges of the Gawler Ranges, and the light areas in the bottom left corner are the Locke Claypans, surrounded by densely vegetated sand-dunes. Wombats are unable to construct warrens along the rocky slopes or in densely vegetated areas, but the population density in the valleys can be very high (as per Figure 3).*

*Warren abundance, size classes and burrow activity*

During the ground truthing survey we marked the position, and measured the attributes, of 736 warrens. These contained a total of 1,863 burrows, of which 1,536 were assessed as active ($\hat{p}$ = 0.82). The mean number of burrows/warren was 2.53 (range: 1 – 20). Warren diameter varied from 1 – 75 m (mean = 9.3 m, σ = 7.8). The number and proportion of warrens of the different size classes were: small - 297 ($\hat{p}$ = 0.38); medium - 314 ($\hat{p}$ = 0.49); large - 117 ($\hat{p}$ = 0.12); very large - 8 ($\hat{p}$ = 0.01). The mean number of active burrows / warren for each size class was: small – 0.96 (σ = 0.40); medium – 1.99 (σ = 1.58); large – 4.52 (σ = 3.18); very large – 9.75 (σ = 3.20). The ratio of active burrows (ab) to warren diameter in meters (d) was: ab = 0.22*d ($R^2$ = 0.49) (Figure 5).

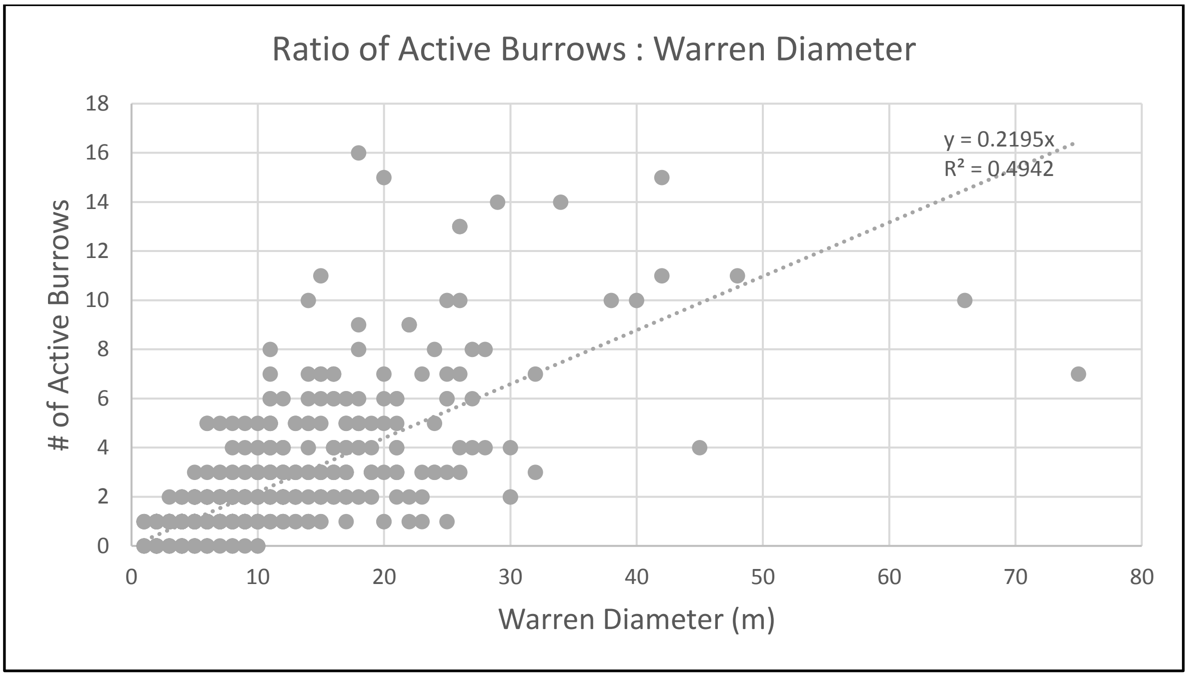


*Figure 5: Number of active burrows / warren and the ratio between the number of active burrows and warren diameter in the Gawler Ranges region - all soil types.*

*Indices for calculating warren densities*

The calculated indices to adjust the satellite imagery warren counts are shown in Table .

*Table 1: Number of southern hairy-nosed wombat warrens of different size classes that were measured in open grassland and closed scrubland during the ground survey transects and from satellite imagery of the same transects in the Gawler Ranges of South Australia. A correction factor (index) is also presented for satellite counts across each warren size class based on comparisons of ground survey and satellite image counts of warrens.*

| Warren Size Class | | Small | | Medium | | Large | | X-large | |
|---|---|---|---|---|---|---|---|---|---|
| | | Ground | Satellite | Ground | Satellite | Ground | Satellite | Ground | Satellite |
| **Open Grass** | # Warrens | 179 | 142 | 187 | 165 | 77 | 77 | 6 | 6 |
| | **Index** | **1.26** | | **1.13** | | **1.00** | | **1.00** | |
| **Closed Scrub** | # Warrens | 54 | 35 | 65 | 45 | 19 | 19 | 3 | 3 |
| | **Index** | **1.54** | | **1.44** | | **1.00** | | **1.00** | |

The mean warren density in the areas populated with wombats was 26.81 warrens/ $km^2$ ($\sigma$ = 20.03), with a maximum warren density of 140 warrens/ $km^2$ to the south of Lake Acraman on Hiltaba (32.06773 S 134.96001 E) and Yardea (32.39243 S 135.38457 E) stations.

*Wombat abundance*

The total number of active burrows in the region was 480,190 ± 14,406. Using indices of 0.32, 0.5 and 0.63 wombats/active burrow, we estimated the median wombat population in the region to be 240,095, with a range of 149,051 – 311,595 (Table 2).

*Table 2: Lower, median and upper estimates of wombat abundance based on the margin of error of the number of active burrows and the index of wombats / active burrow. The index of 0.5 wombats/active burrow used in the median estimate was derived by St John (1998) and used for the previous population estimate for this region. The lower and upper indices were calculated in the Murraylands by Taggart et al. (2012) and Tiver (1981) respectively.*

| | **Lower Estimate** | **Median Estimate** | **Upper Estimate** |
|---|---:|---:|---:|
| **# of Active Burrows** | 465 784 | 480 190 | 494 596 |
| **Wombats / Active Burrow** | 0.32 | 0.5 | 0.63 |
| **# of Wombats** | 149 051 | 240 095 | 311 595 |

## Discussion

The results of our study indicate that there was strong growth in both the distribution and abundance of southern hairy-nosed wombats in the Gawler Ranges region of South Australia between 1988 – 2016. Based on a comparison with survey information collected 1988 the population of wombats appears to have grown from an estimated 14,373 in 1988 to around 240,095 in 2016, and wombats can now be found in areas previously considered devoid of wombats, such as to the east of Lake Harris and extending to the western shore of Lake Gardiner. In this study we found wombats in a variety of different ecosystems, including on sand islands in the middle of Lake Acraman and the Locke Claypans, in soft sandy soil to the east of Lake Everard, in scrubby country to the west of the dingo fence in Yellabinna Regional Reserve, and in the heavy clay soils surrounding the finger lakes on Mt Ive Station. The only areas where we did not find wombats were in the dense scrub to the north of the Lockes Claypans, the hard gibber plains in the northern and central areas, the granite slopes and ridges of the Gawler Ranges proper, and in the soft sandy dunes to the south-west and west of the region.

From conversations that we had with landholders and other residents in the area the expansion in distribution, particularly in the northern part of the region, appears to have been steady since 1988, with locals stating that wombats were expanding northwards and eastwards, and that they were first noticed north of the trans-continental railway line in ~ 2002. This is 15 km north of the range mapped for the species in 1988. Today they can be found up to 30 km north of the railway line (Figure 6).

*Figure 6: Southern hairy-nosed wombat warren adjacent to the transcontinental railway line (in the background of the image), ~20 km west of Kingoonya. This is 15 km north of the distribution in 1988.*

Wombats are relatively slow breeding animals – with females generally able to produce no more than two young every three years (Taggart and Temple-Smith 2008). Although recent studies suggest that there is a female sex bias in the young produced during periods when the population is expanding (Gaughwin *et al.* unpub. data), the large increase in both the distribution and abundance found in this population since the 1980s is astonishing. This suggests that a fundamental change in the ecosystem may have occurred across this period. This growth is even more remarkable given that the region experienced below average annual rainfall for approximately half of the survey period (between 1997 – 2009: the 'millennium drought'), especially during the cooler months (April – November) (BoM 2015) when rain is critical for the growth of the grasses that wombats rely upon to breed and raise young (Gaughwin *et al.* 1998). However, whilst such a sustained population increase over 28 years ~ 10.0 % annual growth rate – appears high, it is not without precedent. In 1971, six southern hairy-nosed wombats were translocated to Wedge Island at the entrance to Spencer Gulf. By 2011, the population had increased to an estimated 300 individuals (Ostendorf *et al.* 2016), which represents a 9.8 % annual growth rate sustained over 40 years.

One factor which could have played a role in the recent increase in wombat numbers in parts of the Gawler Ranges is the conversion of two pastoral properties in the region to fauna and flora conservation. Bon Bon Station is a 2,167 $km^2$ property located in the north-east of the region to the north of the trans-continental railway. It was purchased by Bush Heritage Australia in 2008 and converted from livestock grazing to nature conservation (Blake 2016). The removal of competition from livestock is likely to have favoured wombats; however, the relatively short period between the conversion and this study suggests that any such impact on the overall population would have been minimal. Similarly, the 2012 conversion from sheep grazing to nature conservation of Hiltaba Station, a 780 $km^2$ pastoral property located to the south-west of Lake Acraman (Nankivell 2016), is also too recent to explain the population increases observed in the area between the 1988 and 2016 survey periods. In the early 1960's wombats were described as 'inconspicuous' on Hiltaba Station (Aitken 1971), but were noted as increasing in abundance over the next 25 years (St.John 1998); although the population density was still considered low at the time of the 1988 survey (Figure 2). Interestingly, during our survey we noted population densities on Hiltaba Station of up to 140 wombats / $km^2$ on some areas of the station. This suggests that there has either been a sustained increase in the wombat population on the property over the past 50 years, with a higher growth rate since 1988 (Figure 7), the initial abundance calculations made in 1988 were under-estimated, or both.

*Figure 7: Google Earth satellite imagery of Hiltaba Station in 2005 (left) and 2015 showing the increase in wombat warrens (white dots) in the area.*

Perhaps the most significant change to the ecosystem in the region since the 1980s has been a decline in the rabbit population following the release of the RHDV in the 1990's (Mutze *et al.* 1998) and the recent emergence of RHDV2 (Peacock *et al.* 2017). Rabbits are known to be a significant competitor of wombats (Cooke 1998), and the arrival of rabbits in the nineteenth century is implicated in a substantial decline in wombat numbers across much of their distribution (Swinbourne *et al.* 2017). Whilst there is no definitive data on changes in the rabbit population in the Gawler Ranges because of RHDV, landholders claim that approximately two-thirds of all rabbit warrens in the region are now completely unoccupied, and that even active rabbit warrens contain few active burrows (M. Chuk, pers. comm.). We made similar observations of abandoned rabbit warrens during our field surveys.

Whilst a decrease in competition from rabbits following the release of the RHDV is a logical explanation for the increase in the distribution and abundance of wombats since 1988, it does not explain a reported expansion which occurred in the Lake Acraman group from the 1960s – 1988 (St.John and Saunders 1989). Despite this, rabbit control is also a likely explanation for this expansion, as the release of myxomatosis in the 1950s (Myers *et al.* 1954) and the introduction of rabbit fleas in the 1970s to facilitate the spread and increase the virulence of myxomatosis also suppressed rabbit numbers (Cooke 1983). However, if rabbit control did facilitate an increase in the wombat population around Lake Acraman, this begs the question as to why the Lake Harris population did not experience a similar increase. The explanation previously given for this was possible constraints on burrow construction in the sandy Wirramina soils to the south and west (St.John 1998). However, as we found wombats in these areas during our survey, this explanation now appears unlikely. It also does not explain why the population had not expanded to the north. As we found some of the highest population densities in the region in this northern area around the ephemeral lakes mid-way between Kingoonya and Tarcoola and on the northern shore of Lake Harris, there always was the clear potential for the population to expand in this direction. A more likely explanation is that the local population density in the 1980s was too low for range expansion until it increased above a critical density (Brown 1984). In 1988 the population density across the entire area was assessed as only ~ three wombats / $km^2$, the majority of which could be found in the centre of the distribution (Figure 2) (St.John 1998). We assess that the average population density in the Lake Harris area has now increased to ~ 33 wombats / $km^2$, with up to 110 wombats / $km^2$ in the most densely populated areas.

It is clear from the increase in both distribution and warren density that there has been a large increase in wombat abundance in the Gawler Ranges region since the 1988 survey period. However, quantifying exactly how many wombats there might have been in the region in the past and how many there might be now – and hence determining a definitive population trend - is problematic. Wombats are nocturnal and fossorial, and their cryptic nature makes counting them difficult. Whilst estimating wombat numbers at the local scale can be achieved using measures such as DNA analysis of hair samples (Walker *et al.* 2008) or burrow counters (Taylor 1998), at the broad scale all abundance estimates to date have relied on a proxy measure – an index of the number of wombats / active burrow. However, there are a number of potential sources of error with this approach, including some of the variables in our equations and even determining whether or not a burrow is active (Tartowski and Stelmann 1998). Consequently, even small differences in the indices used can result in large differences to the overall count.

The Gawler Ranges population estimates in the 1980s were based on an index of 0.5 wombats / active burrow to calculate abundance (St.John 1998). This figure was derived by combining two separate indices of 0.60 and 0.43 which were calculated for the Far West Coast region of South Australia (Tiver 1980) and the Murraylands (Tiver 1981) respectively. Interestingly, the 0.43 index for the Murraylands contains a calculation error, and the correct figure should have been 0.63 (48 active burrows / 30 wombats). Similar indices have been used in other population estimates, including a figure of 0.43 used by MacGregor and Wells (1998), based on a study undertaken at Moorunde Wildlife Sanctuary in the Murraylands (Taylor 1998), and 0.32 used by Taggart *et al.* (2012), which was calculated by combining the 0.5 index with a correction factor of 0.64 to account for multiple warren use by individual wombats (Finlayson *et al.* 2005).

Unfortunately, while these figures appear similar, the difference between 0.32 and 0.63 wombats / active burrow represents virtually a 100% difference in abundance calculations. As these indices are therefore sensitive to even slight errors or variations, our estimates of population abundance necessarily include a wide upper and lower limit of potential population sizes. Importantly, whether even this range is sufficient to encompass the correct wombat abundance is open to question, with indices from as low as 0.24 and up to 1.17 wombats / burrow (total burrows, not active burrows) being calculated for Scrubby Creek in the Gawler Ranges (Walker *et al.* 2008) and Kulpara on the Yorke Peninsula (Walker 2004) respectively, and anecdotal reports of up to 1.5 wombats / active burrow in other areas (Stott 1998). This highlights the need for further research to try and determine how best to calculate wombat abundance at the broad-scale.

In addition to the main population group near Lake Acraman and Lake Harris, we observed colonies of wombats on both Bon Bon and Mt Vivian stations to the north-east of Kingoonya on the eastern side of the Stuart Highway, separated from the main population group by up to 30 km, which were not included in the 1988 maps. Isolated colonies such as these, which are too far from the main population group to have recently dispersed to the area, support the idea that the wombat distribution was once more widespread, and the population underwent a contraction at some time in the past. It also suggests that, rather than the recent population expansion representing wombats moving into new areas – as some landholders believe – it is more likely that they are reclaiming territory which they once occupied prior to the rabbit plagues of the early twentieth century (Alpers *et al.* 2016; Swinbourne *et al.* 2017). The large gaps between the isolated and main populations also suggests that there is still a great deal more territory which may be suitable for wombats, and given favourable conditions, the population is likely to continue to expand into these areas in the short to medium term.

The reason that some population groups were not mapped in 1988 is probably due to the remote nature of much of the region. There are few roads or tracks, so conducting ground surveys is highly problematic. In the past, the use of aircraft to survey the more remote parts of the region would have only partially offset this limitation, as the cost associated with detailed aerial surveys is prohibitive, and their use was restricted to high priority search areas only. Further, identifying and counting wombat warrens from an aircraft at that time would have been difficult (Tiver 1981), and it is likely that not all the warrens were observed in some areas. The use of very high-resolution satellite imagery has largely allowed us to overcome these limitations and to survey a wider area more thoroughly. However, despite its benefits, there are also issues with the use of freely available satellite imagery that need to be considered.

The free satellite imagery which is offered via applications such as Bing Maps, Google Earth or ArcMap is usually not the most recent imagery available (the imagery we used dated from May 2014 to May 2016). Although up-to-date satellite imagery can be purchased from commercial organisations, new tasking 50 cm resolution panchromatic imagery covering our full survey area would be prohibitively expensive; costing ~ US$23 / $km^2$ in 2017 (Landinfo 2017) – or over US$1 million for this study alone. Switching between different computer applications (such as Bing Maps and Google Earth) and selecting the most recent imagery from each can offset this to a limited degree.

This study indicates that ground truthing surveys are still essential to determine the scale of any potential changes in the distribution and number of warrens since satellite imagery was captured. To this end, if the wombat population had contracted in the time between the imagery capture date (2014) and our ground survey (2016), we would have expected to have observed abandoned or inactive warrens. As this did not occur – indeed, the proportion of active burrows (0.82) was quite high - we assess that it is highly unlikely that the population declined between 2014 to 2016, and it is more likely that it remained constant or continued to increase. To confirm this and to determine any future population trends, we recommend that more frequent follow-on surveys should be conducted using both ground-based surveys and more up-to-date imagery when it becomes available.

## Conclusion

The marked increase in the southern hairy-nosed wombat population in the Gawler Ranges region suggests that the recent upgrade in the IUCN conservation status of this species may have been premature; especially as this was based primarily on population data from the Murraylands, with only limited and out-of-date information available across much of the remainder of their range.

Whilst acknowledging that this species is highly sensitive to the impacts of drought (Wells 1989; Taggart and Temple-Smith 2008; Marshall *et al.* 2017), and that southern hairy-nosed wombats are a protected species in South Australia, landholders are able to apply for a permit to cull the species on their properties in areas where it is considered overabundant, in order to mitigate any damage that they might cause (DEWNR 2007). If the species were to be listed as threatened, this may impose additional restrictions on their management. However, if the overall wombat population is increasing, as now appears possible, such restrictions would not only be unnecessary for wombat conservation, they could also be detrimental to the environment in the absence of a top order predator (e.g. dingoes) to help regulate population numbers (Banks *et al.* 2003; Letnic *et al.* 2012), and potentially harmful to agriculture (Stott 1998; Sparrow *et al.* 2011).

Consequently, we strongly recommend that research be continued to completely map the overall abundance of the southern hairy-nosed wombat population across its entire distribution, in order to provide accurate and scientifically defendable information to guide future management actions. This should include further research on developing robust indices to refine estimates of wombat abundance across the different regions and ecosystem types.

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## Conflicts of Interest

The authors declare no conflicts of interest.

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# Statement of Authorship

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| Overall percentage (%) | 80% | | |
| Certification: | This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper. | | |
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By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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# Chapter 5: Southern hairy-nosed wombats (*Lasiorhinus latifrons*) in Western Australia: out of sight, out of mind

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## Abstract

*Southern hairy-nosed wombats (Lasiorhinus latifrons) inhabit a fragmented distribution across the arid and semi-arid regions of south / central South Australia and south-eastern Western Australia. Although significant research has been undertaken on the South Australian population, there have never been any broad-scale surveys of wombats in Western Australia. To correct this, the aims of this study were to map the distribution and to estimate the abundance of the Western Australian population of southern hairy-nosed wombats. We undertook two field surveys to speak with landholders in the region, and to map and measure the attributes of selected wombat warrens. We then analysed very-high resolution satellite imagery of the area between the South Australian border and Balladonia, and from the coastline to the transcontinental railway. The distribution of wombats in Western Australia stretches from the South Australian border to Caiguna, and northwards from the Eyre Highway for approximately 75 km. We estimate the population abundance to be between 65,435 and 136,794, with a median estimate of 90,648 to 105,405. All landholders in the region believe that wombat numbers have been increasing over the past few decades. Follow-on research needs to be undertaken in the decades ahead to determine any population trends.*

## Introduction

The effective management of a wildlife species requires a good understanding of its population dynamics, including its distribution, abundance, population trends, and the factors which influence these fundamental traits (Fryxell *et al.* 2014). While the distribution of a wildlife species can cross human political borders (states, territories or nations), research into, and management of, wildlife is often undertaken differently in different jurisdictional regions. These divergent approaches to wildlife management have the potential to result in an incomplete assessment of where a species can be found and/or how many individual animals there might be; with the potential for improper management at the species-wide scale (Bischof *et al.* 2016).

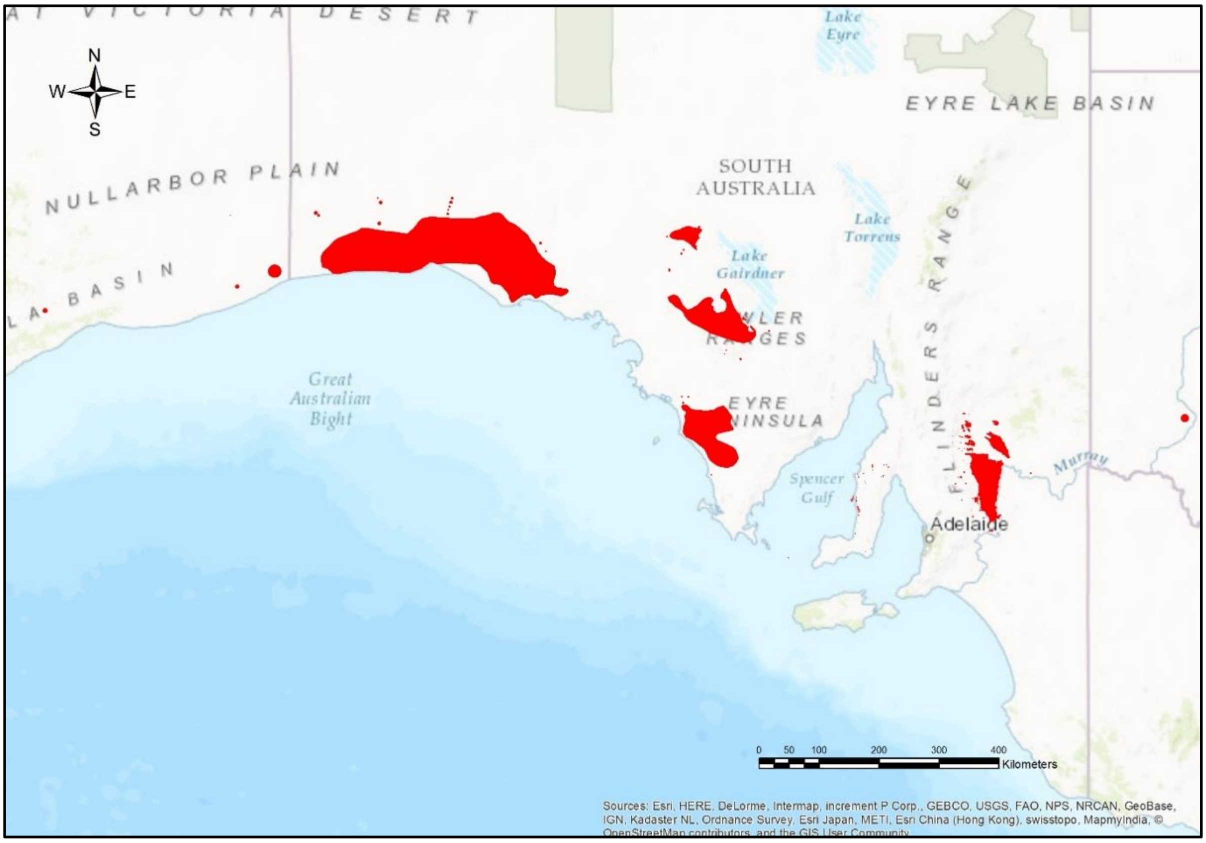


*Figure 1: The distribution of southern hairy-nosed wombats as at the latest published survey for each region. However, this map is significantly out of date, as the information for the Gawler Ranges and Eyre Peninsula regions has not been updated since the 1980s, and there has been no detailed survey undertaken in Western Australia.*

The southern hairy-nosed wombat (*Lasiorhinus latifrons*) is the faunal emblem of South Australia. While wombats currently inhabit a fragmented distribution across the arid and semi-arid regions in the south-central areas of the state (Figure 1), at the time of European settlement they could be found from Euston in New South Wales to as far west as Balladonia in Western Australia (Swinbourne *et al.* 2017). Their numbers declined dramatically across their entire range in the late nineteenth and early twentieth centuries, most likely as a result of competition from rabbits, the modification of land for agriculture, and human persecution. Indeed, in Western Australia by the mid-twentieth century some naturalists were doubting whether wombats had been present in the state in any numbers during European settlement (Jenkins 1962; Lowry 1967). One report by the Western Australian Government’s Department of

Environment and Conservation even suggested that wombats may have been extinct in the state for 30,000 years (Abbott 2009).

The paucity of information regarding wombats in Western Australia is, in one respect, understandable. The Nullarbor Plain, where wombats could be found in the early years of European settlement, contains no settlements other than a few highway roadhouses and isolated agricultural properties. The only major road in the area, the Eyre Highway, was not completely sealed until 1976 (Edmonds 1997), and all access roads between the highway and the transcontinental railway line remain unsealed to this day. Despite these difficulties, occasional reports have been published which support the ongoing presence of wombats at several locations in the region, including Rawlinna station (St.John and Saunders 1989), Caiguna (Lowry 1967), Mundrabilla (Aitken 1973) and Forrest (St.John and Saunders 1989).

The dispersed geographic extent of these reports suggests that wombats may once have been widespread in Western Australia. However, while numerous surveys have been undertaken in South Australia, no broad-area surveys have ever been published of the Western Australian wombat population. Further, while a management plan was formulated for wombats in South Australia (St.John and Saunders 1989), including distribution maps and an overall population estimate, no account was made for wombats in Western Australia and they were not included in the overall abundance estimate. As a consequence, if southern hairy-nosed wombats are present in Western Australia in significant numbers, then our current understanding of the species-wide distribution and abundance would almost certainly understate the true situation.

To update our knowledge of the species-wide distribution and abundance of southern hairy-nosed wombats in Western Australia, we undertook two field surveys to south-eastern Western Australia to ascertain the likely wombat population in the region. The field surveys included holding discussions with landholders and locals in the area, as well as marking the position and measuring the key attributes of warrens in several locations. Based on the knowledge we gained from the field surveys, we then used very-high resolution satellite imagery to map the full distribution of southern hairy-nosed wombats in Western Australia and to estimate their overall abundance.

## Method

*Warren counts and classing*

We conducted two field surveys (May 2016 and May 2017) of the Nullarbor Plain region of Western Australia between the South Australian border westwards to Balladonia, and from the coastline north to the transcontinental railway, to speak with landowners about wombats on their properties and to survey selected warrens in the area (Figure 2). Warren positions were marked with a hand-held GPS (Garmin eTrex 10) and their sizes were estimated by pacing across the diagonal axis. The total number of burrows and the number of active burrows in each warren were counted. Burrows were assessed as active if there were signs of recent digging (within the past few days), wombat footprints, fresh scats, or visual or audible signs of a wombat in the burrow. Measured warrens were separated into four size classes: small (0 – 5 m); medium (6 – 15m); large (16 - 35 m); and very large (> 35 m) (Tiver 1980; Tiver 1981; McGregor and Wells 1998; St. John 1998; Taggart and Ostendorf 2012).

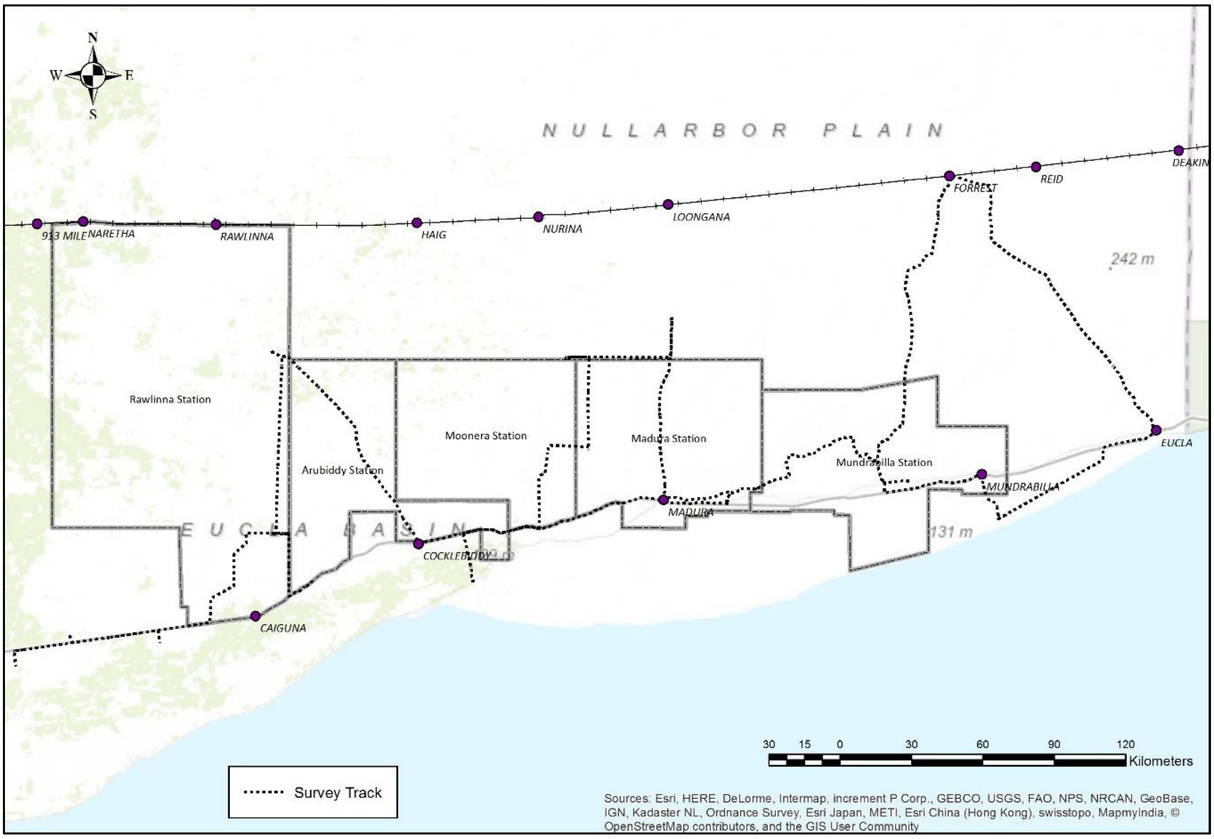


*Figure 2: Nullarbor Plains region of Western Australia showing the main agricultural properties in the area and our survey track. We also analysed satellite imagery which covered the area between the coast and the transcontinental railway line, and from the western to eastern edges of this map.*

*Warren surveys using satellite imagery*

Wombat warrens can be visible on satellite images (Löffler and Margules 1980; Swinbourne *et al.* 2018b). Using freely-available, very high-resolution (better than one metre resolution) satellite imagery on Google Earth and Bing Maps, we used ArcMap version 10.3.1 to overlay a grid of 1 $km^2$ cells oriented north-south over satellite imagery of the Nullarbor Plains region between the transcontinental railway and the coast, and from the South Australian border to 125 E longitude (Figure 2). Lines of cells oriented north-south and east-west at five kilometre intervals were selected from the grid and inspected for the presence of wombat warrens. The cells containing wombat warrens which were closest to the edge of the grid were highlighted, and an outline distribution of the wombat population was drawn.

Using the ArcMap Sampling Design tool, we randomly selected 1,000 grid cells from within the outline distribution for detailed analysis (1,000 out of 21,972 cells = 4.55%, confidence level = 95%, margin of error = 3%). For each selected grid cell the date of the imagery was recorded, the presence or absence of warrens was noted, all warrens were counted and their diameter measured. The raw count of warrens for each size class in each grid square was then multiplied by an index to correct for warrens which may not be visible in the satellite imagery (e.g. under vegetation) (Swinbourne *et al.* 2018b) (Table 1Table ). The adjusted warren counts for each size class were then multiplied by the mean number of active burrows for each size class to provide a total number of active burrows for each grid cell.

$$\text{Grid Cell}_{\text{active burrows}} = \sum (\text{warren size class x Index x mean \# active burrows/size class})$$

*Table 1: Indices used to adjust satellite counts to account for warrens which may not be visible in the imagery.*

| | **Warren Size Class** | | | |
|---|---|---|---|---|
| **Environment Type** | **Small** | **Medium** | **Large** | **X-large** |
| Open Grassland | 1.30 | 1.05 | 1.00 | 1.00 |
| Closed Scrubland | 1.60 | 1.25 | 1.00 | 1.00 |

The active burrow data from all 1,000 randomly selected grid cells was then summed, and extrapolated to provide an overall figure of the number of active burrows for the region.

$$\text{Active Burrows}_{\text{randomcells}} = \sum^{1,000} \text{Grid Cell}_{\text{activeburrows}}$$

$\text{Active Burrows}_{total} = \text{Active Burrows}_{random\ cells} \times (21{,}972/1{,}000)$

*Wombat abundance*

To calculate total wombat abundance ($\text{Wombats}_{total}$), we multiplied the total number of active burrows ($\text{Active Burrows}_{total}$) by indices of 0.32 (Taggart and Ostendorf 2012), 0.43 (McGregor and Wells 1998), 0.5 (St. John 1998) and 0.63 (Tiver 1980) to provide an estimated minimum, median and maximum number of wombats for the region.

$\text{Wombats}_{total} = \text{Active burrows}_{total}\ (0.32, 0.43, 0.5, 0.63)$

**Results**

We found wombats from the South Australia border westwards to Caiguna, a distance of ~ 350 km, and from the Eyre Highway northwards for ~ 75 km. The distribution is patchy, with the highest population densities occurring in the east near Eucla and Mundrabilla within 30 km of the Eyre Highway. In general, wombats only occur to the north of the Eyre Highway, except for a colony mid-way between Cocklebiddy and Madura, and only occur 'above the escarpment', except for the area between the Mundrabilla roadhouse and Mundrabilla station homestead. There is a small outlying colony adjacent to the transcontinental railway line, ~ 5 km to the south-east of the town of Forrest (30.85 S 128.11 E), separated from the main population group by ~ 30 km. (Figure 3)

During the ground surveys we spoke to the landholders / station managers on Rawlinna, Arubiddy, Madura / Moonera and Mundrabilla stations (Figure 2), and marked the position, and measured the attributes, of 492 warrens. These contained a total of 1,140 burrow entrances, of which 831 were assessed as active ($\hat{p} = 0.73$). The mean number of active burrows/warren = 1.69 (range: 1 – 12). Warren diameters varied from 1 – 38 m (mean = 7.5 m, $\sigma = 5.5$). The number of warrens of the different size classes was: small - 229 ($\hat{p} = 0.47$); medium - 221 ($\hat{p} = 0.45$); large - 41 ($\hat{p} = 0.08$); extra-large - 1 ($\hat{p} = 0.00$). The mean number of active burrows / warren for each size class was: small – 0.86 ($\sigma = 0.58$); medium – 2.06 ($\sigma = 1.52$); large – 4.24 ($\sigma = 2.42$); extra-large – N/A ($\sigma$ = N/A) (Table 2).

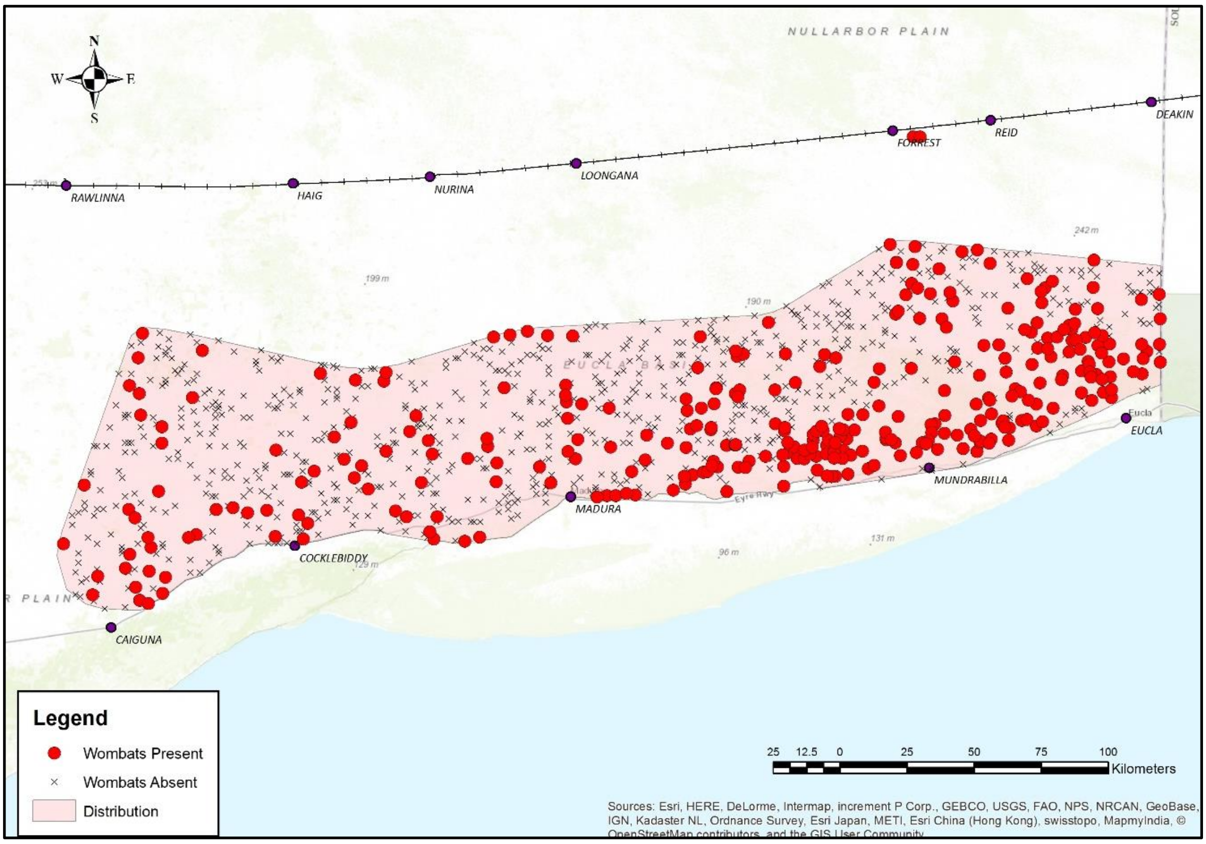


*Figure 3: Distribution of southern hairy-nosed wombats in Western Australia as at July 2017. Note the patchy distribution, with the most densely populated region in the south-east between Eucla and Madura. Each 'Wombats Present' point represents the marked position of one warren selected from within a one square kilometre survey grid. Each 'Wombats Absent' point is the centre of a one square kilometre grid which contains no warrens.*

*Table 2: Characteristics of all warrens of different size classes which we measured during the field surveys.*

| Size Class | Number Surveyed | Proportion of Total | Mean # of Active Burrows | Mean # of Total Burrows |
|---|---|---|---|---|
| **Small (0 – 5 m)** | 229 | 0.47 | 0.86 (σ = 0.58) | 1.22 (σ = 0.65) |
| **Medium (6 – 15 m)** | 221 | 0.45 | 2.06 (σ = 1.52) | 2.90 (σ = 1.71) |
| **Large (16 – 35 m)** | 41 | 0.08 | 4.24 (σ = 2.42) | 5.22 (σ = 2.58) |
| **Extra Large (> 35 m)** | 1 | 0.00 | N/A | N/A |
| **Total** | 492 | 1.00 | 1.69 (σ = 1.62) | 2.32 (σ = 1.87) |

The mean warren density in the populated areas is 23.67 warrens / km$^{-2}$ (σ = 18.57), with a maximum warren density of 96 warrens / km$^{-2}$ in the area ~ 15 km north-west of Eucla, 20 km to the west of the South Australian border. Using indices of 0.32, 0.43, 0.5 and 0.63 wombats /

active burrow, we estimate that the overall wombat population in the region is between 65,435 – 136,794, with a median estimate of 90,648 - 105,405 (Table 3).

*Table 3: Lower, median and upper estimates of wombat abundance based on the margin of error of the number of active burrows, and the index of wombats / active burrow.*

| | Lower Estimate | Median Estimates | | Upper Estimate |
|---|---|---|---|---|
| **# of Active Burrows** | 204 485 | 210,809 | 210,809 | 217 133 |
| **Wombats / Active Burrow** | 0.32 | 0.43 | 0.5 | 0.63 |
| **# of Wombats** | 65 435 | 90,648 | 105,405 | 136 794 |

## Discussion

This study provides the first in-depth assessment of the distribution and abundance of southern hairy-nosed wombats in Western Australia. While previous broad-scale studies of the southern hairy-nosed wombat population have described the South Australian population in detail, information on the Western Australian population has been incidental only. Apart from a few one-off reports (Jenkins 1962; Lowry 1967), the only major study which reported on wombats in Western Australia described the population as consisting of *"outlying colonies… stretching to… Mundrabilla"* and that *"colonies have been reported from as far west as Caiguna, but I have not seen these"* (Aitken 1973).

Our findings show that, while the Western Australian wombat population has remained unsurveyed until this study, it is not an inconsequential population group and it does represent a substantial proportion of the overall species distribution and abundance. The geographic extent of the Western Australian wombat population is similar to that of the Nullarbor / Far West Coast population on the South Australian side of the border, and it occupies similar geographic and climatological niches. The number of wombats in Western Australia is approximately two to three times larger than the most recent published data for the Murraylands region (McGregor and Wells 1998). Given this, we strongly recommend that the Western Australian wombat population be subject to additional research in the future to monitor population changes over time.

While the evidence clearly shows that the wombat population in Western Australia is substantial, wombats are nocturnal and fossorial, and their cryptic nature means that estimating their abundance can be difficult. All regional and species-wide abundance estimates to date have relied on a proxy measure – an index of the number of wombats / active burrow. However, the surveys which have calculated wombat abundance at the regional level have used a range of different indices of wombats / active burrow, and the abundance estimate calculated can vary markedly depending on which index is selected.

The wombat population estimates undertaken in the 1980s, and on which our current understanding of wombat abundance are based, were based on an index of 0.50 wombats / active burrow (St. John 1998). This figure was derived by combining indices of 0.60 and 0.43, which had been calculated for the Far West Coast region of South Australia (Tiver 1980) and the Murraylands (Tiver 1981) respectively. A survey of the Murraylands population in the 1990s (McGregor and Wells 1998) used the lower index of 0.43, which had been separately calculated for the region by Tiver (1980) and Taylor (1998) using two different methodologies. In 2012, the 0.5 index was again used for the Murraylands (Taggart and Ostendorf 2012); however, on this occasion it was adjusted by a correction factor of 0.64 to account for multiple warren use by individual wombats (Finlayson *et al.* 2005), leading to an overall index of 0.32 wombats / active burrow used in the final abundance calculations. The lower (0.32) and higher (0.63) indices which have been used to date represent virtually a 100% difference in potential estimates of wombat abundance, and this highlights the sensitivity of even small errors or variations in the constants used to determine abundance calculations. Because of this, our estimates of population abundance of between 65,435 and 136,794 necessarily include a wide range of potential results.

Whether our estimate of wombat abundance in Western Australia describes an increasing or decreasing population cannot be determined, given that there was no earlier assessment for comparative purposes. However, our conversations with landholders strongly suggest that the population is likely to have been increasing over the past 30 years. For example, in the 1980s the wombat population on Mundrabilla Station, 100 km from the South Australian border, was thought to be in isolated colonies only (Aitken 1973; St.John and Saunders 1989). This assessment was verified by the station owner (B. Campbell pers. comm.), who also suggested that wombat numbers have been increasing on the property ever since, and that the distribution has been expanding both westwards and northwards. Today, the wombat population density on

Mundrabilla Station directly above the escarpment is amongst the highest in the state. The number of wombats in some parts of the station is now so high that the station owner claimed that they no longer mustered cattle on motorbikes because of safety concerns over wombat warrens. In the past 15 years, for the first time in living memory wombats have also appeared ‘below the escarpment’, and they now occur throughout the area north of the Eyre Highway between the roadhouse and the station homestead (20 x 2 km).

The most densely populated region in the state encompasses the area to the north of Mundrabilla and Eucla within a roughly triangular shape with a base of ~ 30 km along the South Australian border, northwards from a point ~ 10 km north of Border Village, then south-westwards for ~ 200 km to Madura (31.90 S 127.02 E). Outside of this area the population is unevenly distributed, with some areas containing no wombats at all, interspersed with regions of relatively high population density, such as along the boundary between Arubiddy and Rawlinna stations (longitude 125.56 E) to the north of Caiguna.

At the local scale, this patchy distribution appears to be heavily influenced by topography. Much of the Nullarbor Plain consists of a mosaic of small catchments, each draining to a depression which has undergone colluvial in-filling to form a clay-pan up to one kilometre wide (Mitchell *et al.* 1979). During both our ground surveys and the analysis of the satellite imagery we noticed that these depressions were strong predictors for warren locations, with warrens often being concentrated around the edges of the claypan (Figure 4). This phenomenon has previously been described in South Australia (Aitken 1973; Löffler and Margules 1980). We suggest that there are several reasons for this observation. Firstly, the soil in the claypans is deeper and more friable than on the surrounding limestone ridges, and is therefore more conducive to burrow construction. Secondly, the limited rain which does fall tends to drain into these depressions, promoting more lush growth of the *Eragrostis setifolia* grasslands (Mitchell *et al.* 1979); thus increasing feed availability. The concentration of warrens around the edges of the depression rather than in the centre is most likely to avoid the possibility of flooding on the floor of the claypan which can occur during periods of high rainfall (Geoscience Australia 2017).

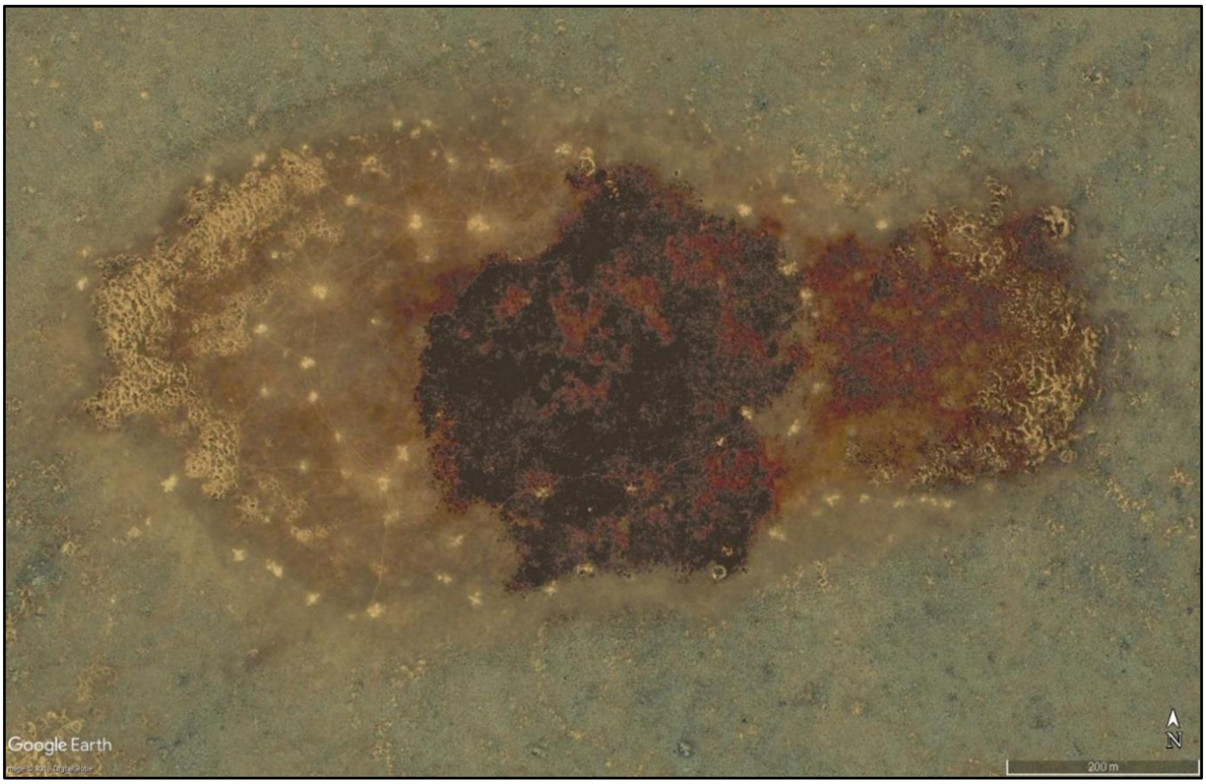


*Figure 4: Satellite image showing wombat warrens constructed around the edges of a claypan depression ~ 45 km north-west of Eucla. The white blotches in the image are the warrens with their interlinking trails. The dark area in the centre of the image is the lowest point of the depression, while the lighter areas to the north and south are the limestone rises surrounding the claypan. Note the lack of warrens in these areas (source: Google Earth 7.3.1.4507. Eucla -31.336084 128.624369, elevation 136M. DigitalGlobe 19 March 2014, accessed 17 March 2018).*

These claypan depressions are widespread across the entire Nullarbor karst region, and extend up to 100 km north of the transcontinental railway. If these areas are favoured by wombats, as appears likely, then there may be scope for the wombat population to expand beyond its current boundaries, as well as to in-fill any vacant claypans within the current distribution.

Further evidence for this potential can be found in an isolated population that we located ~ 5 km south-east of the railway town of Forrest (30.85 S 128.11 E), which is ~ 30 km to the north of the main wombat population group. This distance is probably too great for the wombats to have recently dispersed to the area, and there were unconfirmed reports of wombats in the area in the 1980s. Therefore, it is most likely that the Forrest colony is a remnant group that was left behind when the main population underwent a contraction at some time in the past. The area between Forrest and the main wombat population to the south also contains a large number of claypan depressions (Benbow and Hayball 1992), which suggests that this area is also likely to be suitable for wombats.

Why the wombat population contracted in the past, and why it appears to be expanding now, cannot be determined definitively, although the available evidence suggests that it is most likely related to rabbits. Rabbits are significant competitors of wombats (Cooke 1998), and the rabbit plagues of the early twentieth century have been implicated in the decline of wombats across their entire distribution (Swinbourne *et al.* 2017). Wombat numbers also appear to have been increasing in other regions (Swinbourne *et al.* 2018a) coincident with a long-term reduction in competitive pressure from rabbits as a result of myxomatosis and the rabbit haemorrhagic disease virus (RHDV) (Cooke 1998; Mutze *et al.* 2018). During our field surveys we noted that much of the Nullarbor Plain is heavily infested with rabbit warrens (Figure 5), the majority of which appear to be completely or mostly unoccupied, suggesting that the rabbit population in the region has declined significantly in recent years. If rabbits remain under effective control, we assess that it is highly likely that wombat numbers in Western Australia will continue to increase and that they will expand into areas where they are not currently located.

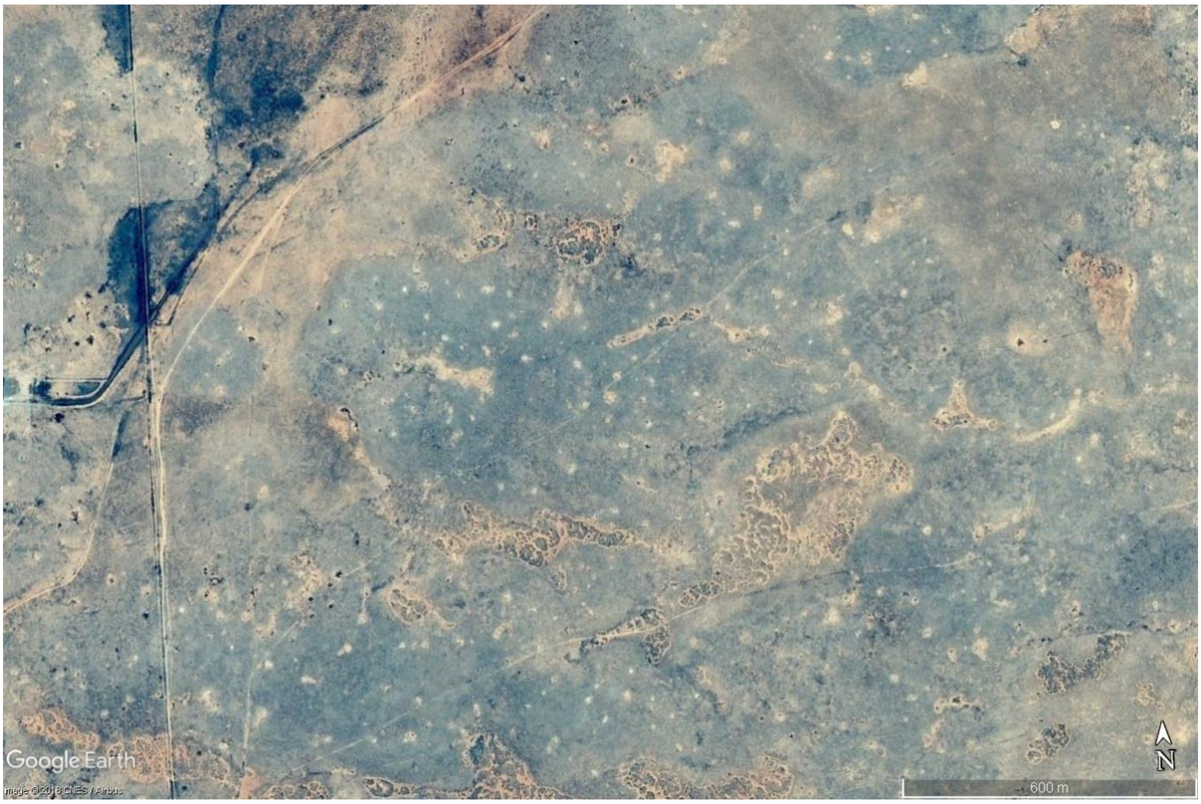


*Figure 5: Satellite image of the area 3 km north-east of the town of Forrest, showing the large number of rabbit warrens (white spots on the image) typical for much of the region. During our field surveys we noted that most of the rabbit warrens on the Nullarbor were either largely or completely unoccupied, which suggests that the population may have declined substantially (source: Google Earth 7.3.1.4507. Forrest -30.838111 128.136605, elevation 157M. CNES/Airbus 24 October 2015, accessed 17 March 2018)*

## Conclusions and Recommendations for Further Research

The findings from this study show that there is a large population of southern hairy-nosed wombats in Western Australia which is comparable with other population groups in South Australia, and which forms a significant proportion of the overall species abundance. The failure to properly account for this population in the past means that all former distribution maps and estimates of wombat numbers are likely to have understated the true situation. This has implications for wombat management at both the regional and species-wide scales, and analysis should be undertaken to determine if any changes should be made to wombat conservation status and management policies. The fact that this has occurred for a large mammal within an industrialised country, and the fact that this relatively large population has remained uncharted until the 21st century, suggests that border and jurisdictional biases may be a more widespread issue that needs closer attention.

Importantly, given that this is the first study to provide a detailed assessment of the distribution and abundance of wombats in Western Australia, we would strongly recommend that follow-on studies be undertaken to establish any population trends.

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**Conflicts of Interest**

The authors declare no conflicts of interest.

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# Statement of Authorship

| | |
|---|---|
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| Contribution to the Paper | Identification of research gap, conceptualisation, study design, research and data collection, analysis, drafting of manuscript, submission and revision | | |
| Overall percentage (%) | 80% | | |
| Certification: | This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper. | | |
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## Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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| Signature | | Date | 8-11-18 |

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| Contribution to the Paper | Supervision, evaluation and editing of the manuscript | | |
| Signature | | Date | 8-11-18 |

# Chapter 6: A search fails to find any evidence for the on-going presence of southern hairy-nosed wombats (*Lasiorhinus latifrons*) in south-western New South Wales

Submitted to: *Australian Mammalogy* 2 August 2018, in review.

**Abstract**

*Following up on two reports from the 1990s, we undertook a ground survey and analysed satellite imagery in order to determine whether there are any extant colonies of southern hairy-nosed wombats in south-western New South Wales. No evidence was found to support the on-going presence of wombats in the region.*

**Introduction**

At the time of European settlement of Australia, southern hairy-nosed wombats (*Lasiorhinus latifrons*) could be found from Balladonia in Western Australia, through the south-central regions of South Australia, and along the northern banks of the Murray River to Euston in New South Wales (NSW) (Swinbourne *et al.* 2017). The distribution underwent a significant contraction in the late nineteenth century, coincident with the opening of the land for agriculture and the spread of rabbits across the landscape. By the early twentieth century they were thought to have disappeared entirely from NSW; although under NSW legislation the species is listed as 'Endangered' in the state (Adams 1997).

In the 1990s reports were received which claimed that there might be two small colonies of southern hairy-nosed wombats - numbering between 2 - 10 individuals each - in the south-western corner of the state; on Tangarry Station and the western shore of Yelta Lake, along the Great Darling Anabranch (NSW Government 2017) (Figure 1). In July 2018 we conducted a search of the reported locations in order to determine whether there were any extant colonies of southern hairy-nosed wombats in the region.


*Figure 1: Satellite image (Google Earth) showing the location of the reported sightings of southern hairy-nosed wombats in south-western NSW in the 1990s.*

## Method

We conducted a search of freely-available (Google Earth and Bing Maps) very-high resolution (DigitalGlobe @ < 1.0 m and CNES / Airbus @ 2.5 m resolution) panchromatic satellite imagery of the region in order to identify any potential wombat warrens within a radius of ~ 5 km from the reported locations (Swinbourne *et al.* 2018). This was followed in July 2018 by a field survey, during which we spoke to the relevant landholders about any knowledge they had regarding wombats on their properties. A ground search was also conducted of a 1 $km^2$ area, centred on the GPS co-ordinates of the earlier reports.

## Results and Discussion

### *Satellite Imagery*

A number of features which appeared to be the warrens of a burrowing species were apparent in the satellite imagery at both locations. However, none had any of the characteristics normally associated with wombat warrens (e.g. interlinking trails) (Swinbourne *et al.* 2018), and all were assessed as most likely to be rabbit warrens.

*Tangarry Station*

The southerly of the two reported wombat sightings was on Talgarry Station, ~ 1.5 km west of Renmark Rd on a low hill in a sheep grazing paddock (Figure 2). We spoke to the landholder (W. Duncan pers. comm.), who was also the landholder at the time of the report, and he claimed to remember it clearly. Mr. Duncan advised that the original report was based on a sighting by a kangaroo shooter. He also claimed that he had not seen a wombat on the property at the time, nor since.

National Parks and Wildlife officers visited the property following the original report, and conducted a hair trapping survey of several warrens. Mr. Duncan accompanied them during this survey, and he recalls that he thought the burrow entrances were too small to be wombat burrows, and were most likely rabbit burrows. During our ground survey we located the remnants of one of these hair traps, and can confirm that it was located on a rabbit warren (Figure 3). While it is possible that the burrow in question was originally a wombat warren that has since collapsed and been re-excavated and occupied by rabbits, we consider this to be unlikely.

We also conducted a ground search of an area of ~ 1 $km^2$, centred on the co-ordinates provided, but could find no evidence of wombats. The reported location is on the northern edge of an area of blue-bush scrub (*Chenopodiaceae*), which is known to be excellent wombat habitat (Aitken 1971; Löffler and Margules 1980). We located several rabbit warrens within the scrub patch and elsewhere throughout the area, but there was no evidence of any active wombat warrens. There were a number of relict warrens in the scrub patch - species unknown – and while we could not discount that they were constructed by wombats, based on the small size of the collapsed burrow entrances, they were also most likely abandoned rabbit warrens.

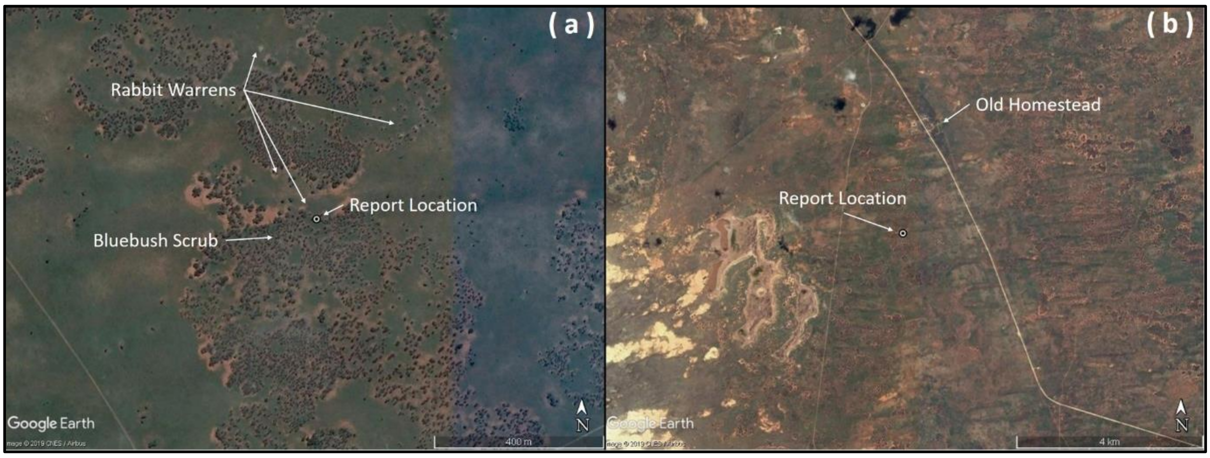


*Figure 2: Satellite imagery of the location of the reported wombat sighting on Talgarry station showing; (a) the area searched during the ground survey, and (b) the area searched using satellite imagery.*

*Figure 3: Remnants of a hair trap at the entrance to a relict rabbit burrow on Talgarry station.*

*Yelta Lake*

The location of the second report is on the western bank of Yelta Lake, ~ 4 km to the east of the Great Darling Anabranch. We spoke to the property owner (Willow Point station – Mr. J. Whyte), but he could not recall the original report. He also stated that he had never seen a wombat on his property.

The exact co-ordinates of the report place it about half-way up the lake bank, which rises ~ 6 m above the surrounding landscape. There were a number of rabbit warrens scattered along the bank, most of which appeared to be either completely or mostly inactive. While there was a warren at the exact GPS co-ordinates of the report which contained two burrow entrances which were larger than normal rabbit burrows, and which could conceivably be large enough for a wombat (Figure 4), there was no evidence of a wombat inhabiting the warren; no scats, footprints or signs of recent digging. One enlarged burrow entrance was inactive (grass growing in the entrance and no signs of recent digging or footprints), and we observed fresh canid tracks at the entrance to the other. On this basis, we concluded that it was most likely being used by a fox or dingo as a den.

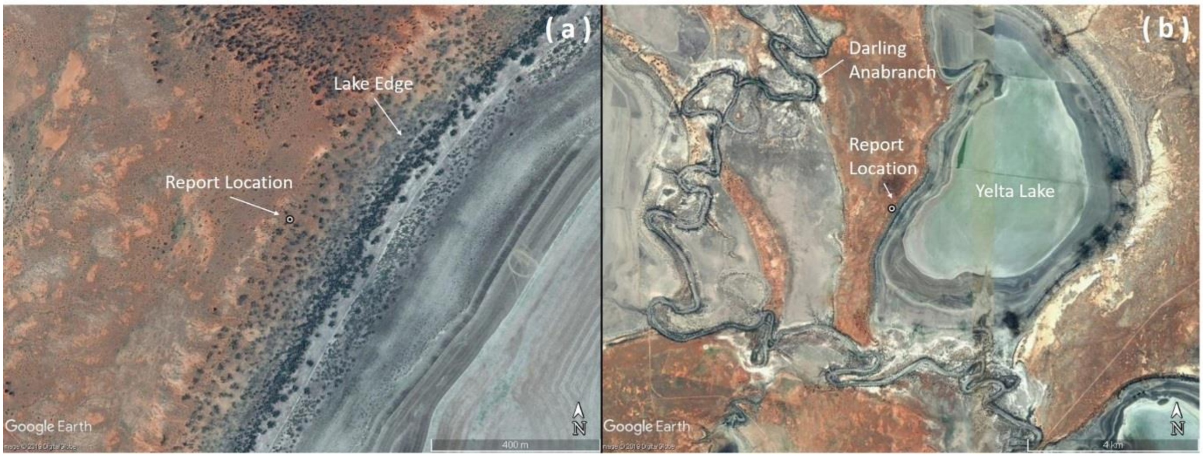


*Figure 4: Satellite imagery of the location of the reported wombat sighting near Yelta Lake showing; (a) the area searched during the ground survey, and (b) the area searched using satellite imagery*

We also searched an area of ~ 1 $km^2$ centred on the co-ordinates provided, but while there were several rabbit warrens in the area, we could find no evidence of wombats. As hairy-nosed wombats use multiple warrens throughout their home range, if the original warren had once been used by wombats, we would have expected to find other warrens with 'wombat-sized holes' in the vicinity. As we found none, and as there were no signs of a wombat using the warren at the reported site, the most likely explanation is that there are none in the area.

## Conclusion

We could find no evidence supporting the on-going presence of wombats in the south-western corner of NSW where they had been previously reported. Indeed, the evidence we did find suggests that at least one of the original reports may not have been accurate. Consequently, unless there is strong evidence to the contrary, the southern hairy-nosed wombat should probably be considered to be extinct in NSW.


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## Conflicts of Interest

The authors declare no conflicts of interest.

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Swinbourne, M. J., Taggart, D. A., Swinbourne, A. M., Lewis, M., and Ostendorf, B. (2018). Using satellite imagery to assess the distribution and abundance of southern hairy-nosed wombats (*Lasiorhinus latifrons*). *Remote Sensing of Environment* **211**, 196-203.

# Statement of Authorship

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| Contribution to the Paper | Identification of research gap, conceptualisation, study design, research and data collection, analysis, drafting of manuscript, submission and revision | | |
| Overall percentage (%) | 80% | | |
| Certification: | This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper. | | |
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**Co-Author Contributions**

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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| Name of Co-Author | David Taggart (co-supervisor) | | |
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| Contribution to the Paper | Supervision, data collection, evaluation and editing of the manuscript | | |
| Signature | | Date | 8-11-18 |

# Chapter 7: A comparison between video and still imagery as a methodology to determine southern hairy-nosed wombat (*Lasiorhinus latifrons*) burrow occupancy rates

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### Abstract

*Broad-scale abundance estimates of the southern hairy-nosed wombat population use a proxy measure based on counting the number of active burrows, which is multiplied by an index of 'wombats / active burrow'. However, the extant indices were calculated in the 1980s, prior to the use of calicivirus to control rabbits, and used invasive monitoring methods which may have affected the results. We hypothesise that the use of video might provide a logistically simple, non-invasive means of calculating updated indices. To this end, motion-activated, infra-red still and video cameras were placed at various distances outside active wombat burrows in the South Australian Murraylands and Eyre Peninsula regions. The captured imagery was inspected to determine how often the burrow was occupied by one or more wombats, and how effective the cameras were at detecting wombat activity. Video data was clearly superior to the still imagery, with more than twice as many burrow occupancies being positively identified (still: 43%). The indices of wombats / active burrow calculated based on video imagery were: Murraylands: 0.43, Eyre Peninsula: 0.42. 1,948 false positive videos were recorded, of which 1,674 (86%) occurred between noon and sunset.*

### Introduction

Southern hairy-nosed wombats (*Lasiorhinus latifrons*) inhabit a fragmented distribution across the semi-arid regions of south-central South Australia and the south-eastern corner of Western Australia (Figure 1). While recent studies have been able to map the species-wide distribution of southern hairy-nosed wombats using very high-resolution satellite imagery (Swinbourne *et al.* 2018), determining how many wombats there might be is more problematic (McGregor and Wells 1998; St. John 1998; Taggart and Ostendorf 2012). Wombat abundance at the broad-scale is estimated by using a proxy measure of counting the number of active burrows (burrows which are currently being used by wombats), which is then multiplied by an index of the number of wombats / active burrow. However, there are several problems with this approach.

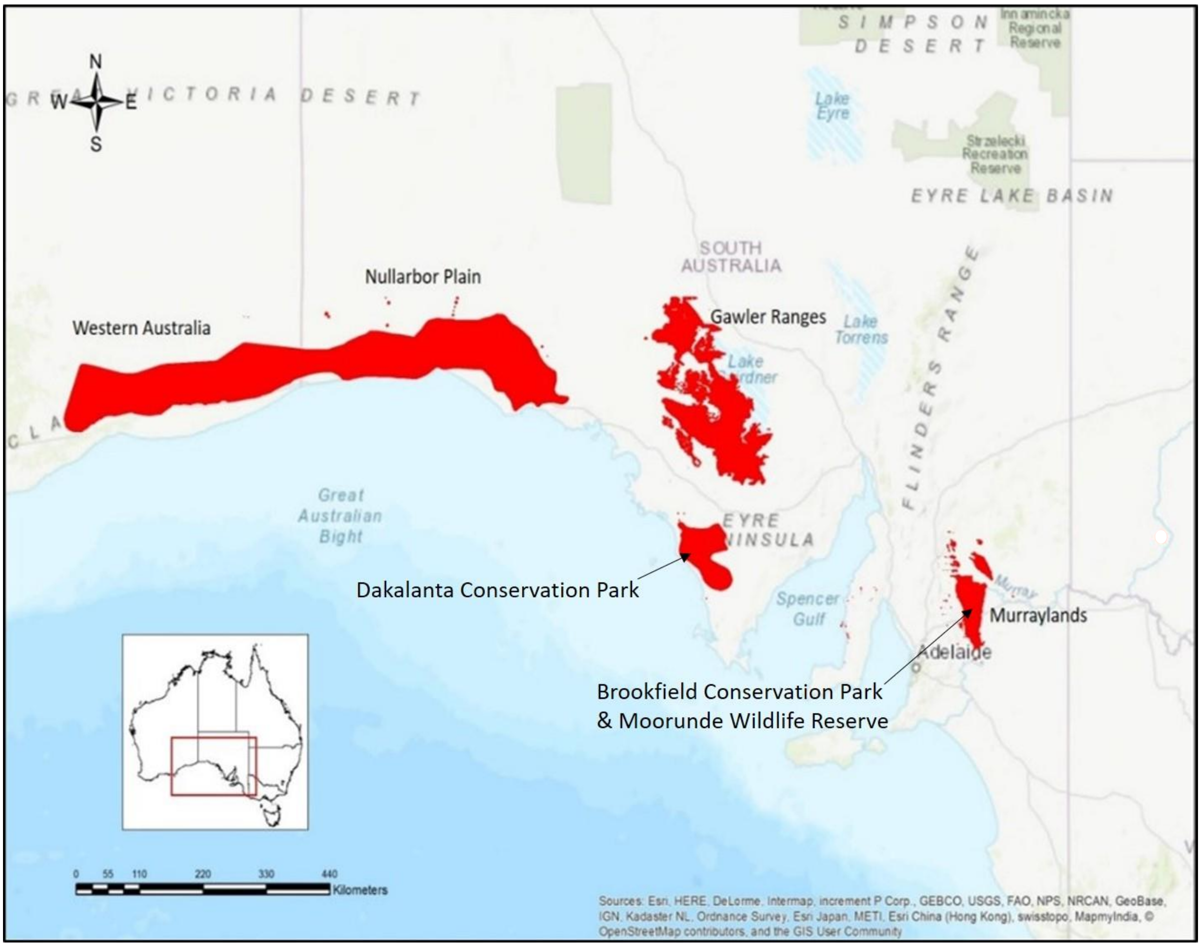


*Figure 1: Distribution of southern hairy-nosed wombats as at the most recent assessments in 2016-18 (Swinbourne et al. 2018).*

Indices of the number of wombats / active burrow were first calculated in the 1980s based on mark-recapture studies using cage traps installed at burrow entrances, which were conducted near Fowlers Bay on the west coast of South Australia (Tiver 1980) and near Blanchetown in the Murraylands (Tiver 1981). The number of individual wombats caught in the traps were counted, and the result was divided by the number of active burrows being surveyed. Whilst hairy-nosed wombats generally have a preferred warren in which they reside for the majority of the time, they also use up to ten different warrens throughout their home range (Finlayson *et al.* 2005). As a consequence, indices of the number of wombats / active burrow based on how many individual wombats there may be in a warren could potentially over-estimate the index by counting not only the wombats which regularly reside in the warren, but also wombats who were visiting from nearby warrens. The use of invasive approaches such as cage traps and mark-recapture surveys also have the potential to skew the results, as wombats will adopt measures such as remaining in their burrows for up to 10 days to avoid the traps (Taggart *et al.* 2003).

We hypothesise that, rather than attempting to identify the number of wombats in an area and then relating that to the number of active burrows (i.e. the object of the study being the number of wombats), a more accurate assessment of the number of wombats / active burrow can be obtained by determining the proportion of active burrows which are being simultaneously occupied by wombats (i.e. the object of the study is the burrow occupancy rate). To achieve this, a reliable method of determining when wombats enter and exit each burrow, and how many wombats are using the burrow at the same time, is required; one which does so non-invasively to minimise any changes in the animals' behaviour.

Motion-activated infra-red cameras (camera traps / wildlife trail cameras) offer a relatively cheap and logistically simple means of monitoring wildlife behaviour (McCallum 2013). The use of motion-activated cameras for wildlife research in Australia has increased significantly over the past decade, with an exponential increase in the number of published papers since 2010 describing the use of camera traps (Meek *et al.* 2015b). Whilst much of the increase in use of motion-activated cameras can be attributed to improvements in the capability and reductions in the cost of the cameras, improvements in both the capacity and cost of data storage has also been important (Shannon *et al.* 2014). Wildlife trail cameras can now capture and store tens of thousands of high-resolution day or night-time images, meaning that they can be left in place longer and can collect more data than earlier camera models. The growth in data storage capacity has also facilitated the greater use of video to analyse wildlife behaviour. This has allowed a greater range and a more accurate interpretation of animal behaviour than would otherwise be possible using still imagery alone (Walter 2015). However, while still imagery has been used on a number of occasions for wombat research (Taggart and Ostendorf 2012), there has been no published research on the use of video to monitor wombat behaviour in the wild.

The aims of this study were to compare the effectiveness of video and still imagery for determining how often the active burrows of southern hairy nosed wombats are utilised, and to use video and still imagery to calculate an index of the number of wombats / active burrow based on burrow occupancy rates.

## Materials and Methods

This study was conducted in two phases. Phase one was conducted in the Murraylands region of South Australia in late spring / early summer 2017. The results from Phase one were analysed and used to refine the camera settings for the Phase two, which was conducted on the Eyre Peninsula during autumn 2018.

### *Phase 1: Murraylands region*

Phase 1 was conducted in the South Australian Murraylands region at two locations - the Moorunde Wildlife Reserve (34.41 S, 139.49 E) and the Brookfield Conservation Park (34.36 S, 139.49 E) - from 17 October to 12 November, and 15 November to 10 December 2017 respectively. Five active wombat burrows were selected at each location (ten active burrows overall) (Table 1). Burrows were considered active if there were signs of recent diggings (the past few days), fresh scats or footprints, or visual or audible signs of a wombat in the burrow. At each burrow, six Shenzhen Byhann BH-H801WP trail cameras, each with 32 Gb of data storage capacity, were mounted on three poles (two cameras - one still and one video – per pole), for a total of 30 cameras (15 video and 15 still) at each location. The cameras were attached to the pole one above the other (order determined randomly), with the lower camera approximately 60 cm from the ground. One pole (close-up) was installed on the spoil mound ~ 2 m from, and angled to face directly into, the burrow entrance. A second pole (medium-range) was located 3 – 5 m to the side of the burrow, and a third (long-range) was located 8 – 10 m from the burrow to obtain an overall view of the warren area (Figure 2). In order to minimise interference to the animals' behaviour, we avoided positioning the camera poles on any burrow entry / exit paths or inter / intra-warren trails.

*Table 1: Survey burrows. Whilst some sites were 'stand-alone', with only one burrow being surveyed and one camera 'group' on each warren, the Brookfield sites ([1]and [2]) had more than one survey burrow per warren.*

| | Site # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Moorunde | Warren Diameter (m) | 10 | 13 | 11 | 15 | 12 | | | | | |
| | No. of Active Burrows | 1 | 2 | 3 | 4 | 5 | | | | | |
| | No. of Burrows | 3 | 5 | 6 | 8 | 6 | | | | | |
| Brookfield | Warren Diameter (m) | 22 [1] | 22 [1] | 22 [1] | 17 [2] | 17 [2] | | | | | |
| | No. of Active Burrows | 4 | 4 | 4 | 3 | 3 | | | | | |
| | No. of Burrows | 12 | 12 | 12 | 10 | 10 | | | | | |
| Dakalanta | Warren Diameter (m) | 11 | 13 | 6 | 16 | 12 | 9 | 14 | 19 | 5 | 7 |
| | No. of Active Burrows | 2 | 2 | 1 | 5 | 2 | 2 | 3 | 4 | 1 | 1 |
| | No. of Burrows | 4 | 3 | 1 | 6 | 5 | 3 | 8 | 6 | 1 | 1 |

*Figure 2: Camera set-up at Site # 5, Moorunde Wildlife Reserve. Each pole has two cameras - one still and one video (six cameras total at each site), with all cameras aimed at the burrow crater in the foreground. The close-up cameras are on the right side of the image, the medium-range are in the centre, and the long-range cameras are on the left.*

The still camera was configured to capture three x five-megapixel images (2,592 x 1,944 pixels) each time the camera was triggered, with a pause of five seconds between image sequences. These settings were the maximum number of images per sequence and the shortest pause time available on the camera. The video camera was configured to take a one-minute 720P video (1,280 x 720 pixels) each time the camera was triggered, with a pause of five seconds between subsequent recordings. The manufacturer's claimed triggering speed of the cameras was 0.6 seconds.

*Data Analysis*

The first two days of imagery from each location were discarded to reduce any potential bias in the wombats' behaviour which may have been caused by disturbance during the installation of the cameras (Taylor 1998). As wombats can remain underground for long periods to avoid detection, we required a minimum of 10 days of recorded images from at least one camera for a site to be considered for detailed analysis (Finlayson *et al.* 2010). The captured imagery was analysed by separating the images and videos into those that contained wombats, those that were triggered by animals other than wombats, and those for which no obvious triggering mechanism was apparent ('false positives').

The time and date of all the images and videos which contained wombats and all false positive videos were then noted and collated. We then examined all the wombat images and videos to determine whether we could positively identify a wombat entering or exiting a burrow, or whether they showed other activity unrelated to burrow entry / exit. We also examined the imagery to determine whether the burrow was being occupied by more than one wombat simultaneously. Only adult wombats were counted; joeys were excluded from our calculations. As wombats are nocturnal, we would generally expect them to exit the burrow in the late afternoon / evening, potentially visit other burrows during their active period or re-enter their original burrow across the night and then finally re-enter a burrow in the early morning where they would shelter during the day. We therefore considered a burrow to be occupied if there was evidence of a wombat entering the burrow in the morning and remaining inside during the middle of the day. The results were collated by camera pairings (close-up versus medium-range versus long-range) and by video versus still cameras.

All data was collated on a Microsoft Excel spreadsheet (2013 version 15), and statistical tests were conducted using the 'Data Analysis' tools add-in. The 'Burrow Occupation Rate' for each burrow was calculated by the dividing the number of days each burrow was occupied by one or more wombats by the number of valid observation days for that burrow. The 'Wombat Occupancy Rate' was calculated in the same manner as the 'Burrow Occupancy Rate', but was adjusted to take into account days when the burrow was occupied by more than one wombat simultaneously. The overall occupancy rate for each survey location was calculated by pooling the data for all burrows at that location, to account for any variations in the number of observation days per burrow. The 'false positives' for all video cameras were pooled and collated by time of day when they occurred.

Data from the camera positions (close vs medium vs long-range) and camera types (video vs still) were compared using a non-parametric test for related samples. The data was initially checked for normality (skewness and kurtosis), then analysed using the Wilcoxon signed-rank test for two related samples.

*Phase 2: Eyre Peninsula*

Phase 2 was conducted at the Dakalanta Conservation Park (33.46 S, 135.34 E) on the Eyre Peninsula of South Australia, from 10 May to 7 June 2018. Ten active wombat burrows were selected for monitoring (Table 1).

Only the close and medium range video cameras were used; the long-range cameras and the still cameras were dispensed with. The camera settings were changed from those used during phase one to reduce the resolution of the video from 720P to 320 x 240 pixels. The cameras were also set to revert to standby mode between 10:30 and 14:30 hours each day, with no video recorded during that time. A single still camera was also mounted on the same pole as the 'medium' video camera, and was set to capture imagery between 10:00 – 15:00 each day (i.e. during the time that the video cameras were in standby mode). This camera was used solely to confirm that no animals had left the warrens whilst the video cameras were in standby mode. The same analysis methodology which was used during phase one was also used during this phase, except the analysis of false positives was not conducted at this site.

## Results

*Phase 1*

Although we installed cameras at five burrow sites in both locations in the Murraylands (ten sites overall), all six cameras at one site (Brookfield site #5) did not operate as they were not switched on correctly (set to 'test' instead of 'on'). Of the nine remaining sites (54 cameras), ten video cameras stopped recording before the end of the survey period due to the data storage capacity (32 Gb) being reached (Moorunde site #1 long – 9 days; site #3 close – 9 days; site #3 long – 5 days; site #4 close – 14 days; site #4 long – 19 days; site #5 close – 13 days; site #5 medium – 16 days; Brookfield site #2 close – 14 days; Brookfield site #3 close – 22 days; Brookfield site #4 close – 21 days).

In total over 15,000 still images and videos were captured for analysis, of which 509 videos and 948 still images were of wombat activity. There were 1,948 false positive videos which did not appear to have any obvious triggering event within the field of view.

We were able to positively identify 92 instances of a burrow being occupied from the video or still imagery. All 92 of these burrow occupancies could be confirmed on the video imagery, whereas we could only positively confirm 40 (43%) from the still imagery (Wilcoxon signed rank test $Z = -2.032$, $p = .042$). The distance at which the cameras were installed from the burrow entrance also affected our ability to identify whether a burrow was occupied. The cameras situated close to the burrow entrance successfully identified that a burrow was occupied on 71/92 occasions (77%) versus 60/92 for the medium-range cameras (65%) and 23/92 (25%) for the long-range cameras. A Wilcoxon signed-rank test showed that there was no significant difference between the close-up and the medium-range cameras ($Z = -.339$, $p = .735$), but there was a significant reduction in our ability to positively confirm burrow occupancy from images derived from the long-range cameras ($Z = -2.371$, $p = .018$) (Figure 3).

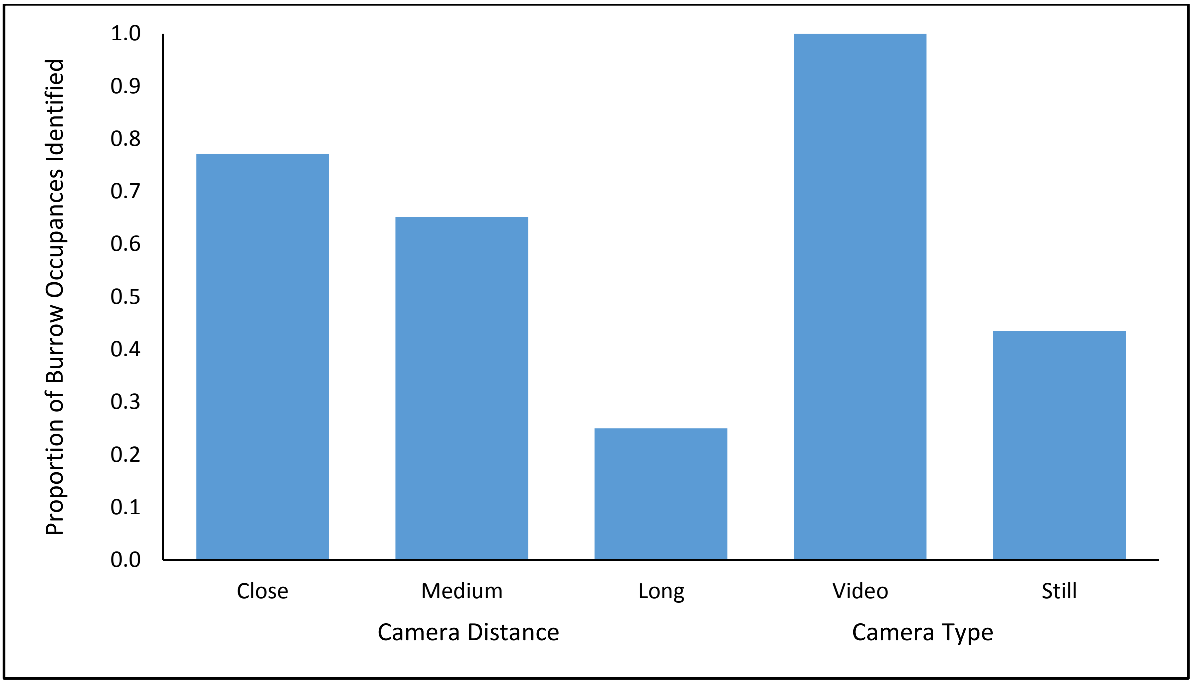


*Figure 3: The proportion of burrow occupancies (entry into or exit from a burrow which provided positive evidence of a wombat occupying the burrow during the day) which we could identify from imagery recorded on different camera combinations.*

Eight out of nine of the burrows for which we had data were occupied by a wombat or wombats at some time during the survey period. The occupancy rate varied from 0% (burrow assessed as active but not occupied at any time during the survey period) to 88% (burrow occupied for 22/25 days). Of the eight burrows which were occupied, two were occupied for less than 25% of the time (12% and 24%), two were occupied for 25 – 50% of the time (32% and 40%), three were occupied for 50 – 75% of the time (56, 56, 60%), and one was occupied for more than 75% of the time (88%). Two burrows (Moorunde sites #4 and #5), were occupied by two wombats simultaneously for a total of two and three days respectively (Figure 4) (Table 2).


*Figure 4: Video captures from the close-up video camera at Moorunde site #4 showing an example of simultaneous burrow sharing by two wombats. In the left image (captured from video # 0132), a wombat enters the burrow at 05:12. Twenty-four minutes later at 05:36, recorded on the subsequent video (# 0133), a second wombat enters the same burrow.*

*Table 2: Proportion of days during the survey period when the surveyed burrow was occupied by one or more wombats, and the wombat occupancy rate. Four burrows (Moorunde sites # 4 and 5 and Dakalanta sites # 2 and 3) were occupied by more than one wombat on two, three, twelve and three days respectively.*

| | **Site #** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | $\bar{x}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Moorunde | Burrow Occupied | 0.00 | 0.56 | 0.12 | 0.60 | 0.88 | | | | | | 0.43 |
| | Wombat Occupancy | 0.00 | 0.56 | 0.12 | 0.68 | 1.00 | | | | | | 0.47 |
| Brookfield | Burrow Occupied | 0.40 | 0.24 | 0.32 | 0.56 | - | | | | | | 0.38 |
| | Wombat Occupancy | 0.40 | 0.24 | 0.32 | 0.56 | - | | | | | | 0.38 |
| Dakalanta | Burrow Occupied | 0.00 | 1.00 | 0.76 | - | 0.08 | 0.40 | 0.08 | 0.40 | 0.28 | 0.25 | 0.35 |
| | Wombat Occupancy | 0.00 | 1.72 | 0.88 | - | 0.08 | 0.40 | 0.08 | 0.40 | 0.28 | 0.25 | 0.42 |

The burrow occupancy rate – the proportion of burrows which were occupied at any one time – during this phase of the study was 0.41 (SD = 0.26). The wombat occupancy rate, and hence the index of wombats / active burrow for the Murraylands, was 0.43 (SD = 0.29).

Of the 1,948 false positive videos, 1,464 were from Moorunde and 484 were from Brookfield. 1,674 of the false positive videos (86%) occurred in the afternoon between 12:00 and 18:00, with only 27 (2%) occurring at night between 20:00 and 06:00 (Figure 5).

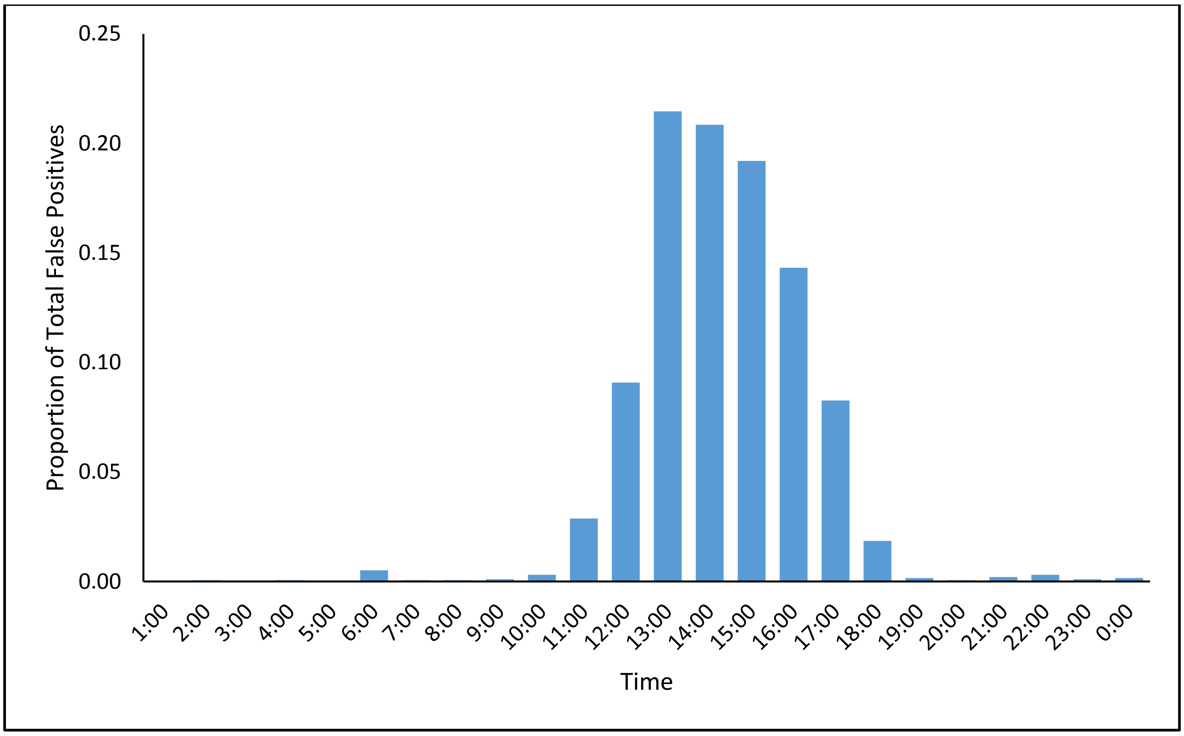


*Figure 5: Proportion of false positive videos (videos for which there was no obvious triggering event and for which there was no animal visible in the field of view) by time of day. Over 85% of all false positive videos occurred in the afternoon between 12:00 and 18:00, with 95% occurring between 11:00 and 18:00.*

*Phase 2*

Although we installed cameras on ten burrows, the cameras on one burrow (site #4) were dislodged by a herd of deer after six days of operation, leaving only four days of valid observations. This site was therefore discarded from further analysis. A second set of cameras (site #10) was also dislodged by the deer after 14 days of operation, but as this provided 12 days of data this site was included in our analysis. Seven of the remaining eight sites provided a full 25 days of data for analysis, with the data storage capacity of the cameras at the remaining site (site # 2) being filled after 20 days (18 days of data for analysis).

Eight out of nine burrows for which we had valid data were occupied by a wombat or wombats at some time during the survey period. The burrow usage rate – the proportion of days when the burrow was in use by one or more wombats - varied from 0% (site # 1: burrow assessed as active but not occupied at any time during the survey period) to 100% (site # 2: burrow occupied every day during the survey period). Of the eight burrows which were occupied, two were occupied for less than 25% of the time (both at 8%), four were occupied for 25 – 50% of the time (25%, 28%, 40%, 40%), none were occupied for 50 – 75% of the time, and two were occupied for more than 75% of the time (76% and 100%) (Table 2). Two burrows (sites # 2 and # 3), were occupied simultaneously by more than one wombat for twelve and three days respectively.

The mean burrow occupancy rate – the proportion of burrows which were occupied at any one time – during this phase of the study was 0.35 (SD = 0.33). The overall wombat occupancy rate – the mean number of wombats / active burrow - for the Eyre Peninsula, was 0.42 (SD = 0.54).

**Discussion**

This study informs two important areas of wombat population research; the reliability of cameras as tools for monitoring wombat activity, and the calculation of an index of the number of wombats / active burrow for use in population abundance estimates. Our results provide evidence for the efficacy of video as a tool for determining warren occupancy rates, albeit with some limitations. They also provide lessons in regard to understanding how the cameras work, and ensuring that they are properly sited and the correct settings are used.

Comparisons between the video and still imagery collected during phase one of this study indicated that there was a clear difference in our ability to positively identify wombat burrow occupancy from video versus the still imagery. The identification of burrow occupancy from video was relatively simple, whilst the approach used in previous studies of identifying individual wombats from still imagery can be difficult and time consuming, with identification relying on characteristics (nose hair patterns, scars, ear notches, etc.) that are not always visible in the imagery. Further, because wombats do not just reside in one warren, but will use up to ten different warrens throughout their home range (Finlayson *et al.* 2005), accounting for wombats which might be 'just visiting' a warren, as opposed to being a resident of that warren, is problematic. We have cases where we have counted over 30 different wombats using 14 burrows over a period of one month; which equates to > 2 wombats / active burrow. Consequently, counting wombats would clearly require more detailed statistical analysis than just assessing burrow occupancy in order to produce accurate abundance estimates.

The failure of the long-range cameras to contribute much useful information during phase one of the study (25% of burrow occupancies identified) highlights some of the limitations with using cameras for this type of research (Meek *et al.* 2015a). There were numerous occasions when data was captured on the close-up and medium-range cameras, but nothing was recorded on the long-range cameras. This suggests that the distance (~ 10 m) may have been beyond the cameras' range, despite the manufacturers claiming a detection range of up to 20 m. We suggest that this is probably only applicable to larger animals, as we did not observe wombats at anything approaching that distance.

The Passive Infra-Red (PIR) sensors used on these cameras detect the surface temperature of objects in the field of view, and trigger the camera when a change in temperature is detected in part or all of the sensor (Welbourne *et al.* 2016). This occurs when an object with a different surface temperature to its surrounds changes its aspect in relation to the sensor (i.e. moves across the field of view). However, the cameras sometimes trigger when there is no obvious target within their field-of-view. We noted that this phenomenon was particularly prevalent during the daytime, with 86% of all false positive detections that we recorded occurring in the afternoon, and less than 2 % occurring at night. Although we did not analyse the false positive rate for phase two, given that we set the cameras to revert to standby mode between 10:30 and 14:30 each day, we noticed that there were few false positive video recordings on any of these cameras, and of the few that did occur, almost all were between 14:30 and 18:00.

Whilst previous studies have suggested that these false positives may be triggered by the wind moving vegetation within the field-of-view of the camera (Newey *et al.* 2015), our results suggest that other factors may have a greater effect. For example, we noticed that while false positives did occur frequently on windy days, they also occurred at a similar rate on still days when neither the camera nor branches were in motion. The increasing number of false positives which occurred as the day progressed and the lower rate of false positives recorded during the night suggests that it may be solar radiation causing the uneven heating of the ground in front of the camera, or heating of the camera body itself, which causes the cameras to trigger. We recommend that further research and pre-survey trials be conducted before undertaking future wildlife studies of this nature, to verify the causes and rate of false positives for the particular camera model being used.

The high rate of false positives, coupled with the data requirements of high-definition (720P) video, meant that we used up the data storage capacity (32Gb) of some of the video cameras before the end of the planned survey period during phase one of the study. As a consequence, we reduced the resolution of the videos to the minimum size possible on the cameras (320 x 480P) to reduce the data storage requirements for phase two of the study. Whilst this largely solved the problem of data capacity, the high volume of wombat traffic at one site (Dakalanta site #2) still resulted in the data capacity of the cameras at that site being used up after 20 days. This highlights the need to carefully evaluate the potential volume of data which may be captured by a camera and the data storage capacity available, and to adjust the camera settings, survey periods and logistics of any study to ensure that data is not missed as a result of inadequate data storage capacity.

In regard to the siting of the cameras around warrens, in the case of a wombat emerging from its burrow there would be only a limited aspect change in relation to the camera oriented directly into the burrow (i.e. the close-up camera). The surface temperature of the wombat's body is also likely to be similar to the ambient temperature of the burrow, especially when the wombat is covered in dirt and the weather is warm. This suggests that fossorial species such as wombats may represent a poor target for PIR detection. There was evidence for this in our observations of burrow entry / exit. Although we generally observed the entire burrow entry process from the video (the wombat approaching, descending into the burrow crater and entering the burrow), in the case of burrow exits the camera usually did not trigger until the wombat had completely emerged from the burrow and was climbing out of the crater (i.e. we rarely observed the wombat inside the mouth of the burrow). We also noted cases where imagery of a wombat exiting the burrow would be captured on the medium-range camera, which was oriented side-on to the burrow entrance, but no imagery was captured on the close-up camera (Figure 6). This phenomenon of cameras failing to detect animals which were within their field of view has been previously described, with up to 68% of verified animal activity being missed in some circumstances (Newey *et al.* 2015).


*Figure 6: Whilst this image of a wombat emerging from its burrow was captured on both the medium-range video and still cameras (medium-range still camera image shown) – which were oriented side-on to the burrow entrance - it was not recorded on either of the short-range cameras (the pole in the image) which were facing directly at the burrow entrance. This highlights the potential for single camera studies to fail to capture imagery of some animals even if they are clearly within their field-of-view, and for the need to consider the orientation of cameras in relation to expected target motion.*

Whether the failure of some of our cameras to detect wombat activity which was occurring within their field of view - and which was captured on other cameras with a different orientation to the target - is an inherent limitation of wildlife trail cameras, or whether it is a limitation of these type of cheaper, generic cameras which are entering the market is difficult to tell from our data. In either case, our findings provide strong support for the importance of understanding the capabilities and limitations of motion-activated infra-red cameras in general, and of the model of camera being used, prior to their use in studies of this type. It also underscores the importance of the correct placement and alignment of the camera in relation to the target and to minimise the potential for false triggers to occur (Meek *et al.* 2015a). Unfortunately, it may not be possible to overcome all the potential limitations with a single camera no matter its quality or how well it is sited, and hence multiple cameras located in different positions may be necessary in some situations. If this is the case, it raises questions about the findings from previous studies where only one camera was used to detect animal presence / activity, and whether some data might have been missed as a result. We recommend further research in this area.

In regard to our calculation of the number of wombats / active burrow, our figure of 0.43 for the Murraylands is virtually identical to previous figures calculated for the region of 0.43 (Tiver 1981), 0.4389 (McGregor and Wells 1998; Taylor 1998) and 0.40 (Porter-Dabrowski *et al.* 2017). The figure of 0.42 for the Eyre Peninsula is the first index which has been calculated for that area. Both figures are lower than 0.60 calculated for the Far West Coast (Tiver 1980) and 0.50 which was used for the only species-wide abundance estimates undertaken to date (St.John and Saunders 1989).

Whilst other studies suggest that a range of indices are required for different conditions such as soil type, especially for small-scale population estimates in areas with a large number of calcrete warrens (Taggart and Ostendorf 2012; Swinbourne *et al.* 2015), the remarkable similarity between the figures we calculated for the Murraylands and Eyre Peninsula suggests that, at the broad scale at least, an index of ~ 0.43 might be a robust figure to calculate wombat abundance. Nonetheless, as this issue is fundamental to our understanding of wombat abundance at both the local and broad scales, we would recommend on-going research to validate these findings, especially in regions other than those previously surveyed and / or under a range of environmental conditions such as drought (Taylor 1998; Marshall *et al.* 2017).

Our results also highlight the difficulties with accurately assessing whether a burrow is active, an issue which has been previously identified in multiple studies (Tiver 1981; Tartowski and Stelmann 1998; Taylor 1998). Two survey sites, site # 1 at Moorunde and site # 1 at Dakalanta were both assessed as active, based on recent diggings and fresh wombat scats around the burrow entrances. However, whilst we observed wombat activity in the vicinity of the burrow entrance at both sites throughout several nights during the survey period, as well as activity by other species including kangaroos and feral goats, there was no evidence on the imagery of a wombat entering or exiting either burrows at any time during the survey. It appears that activity by both visiting wombats and non-target species around the entrance to the burrows disturbed the soil, and together with the deposition of scats, resulted in the misidentification of the burrows' status. We also noted the phenomenon at other survey sites. For example, although the burrow occupation rate for Dakalanta site #5 was only 0.08 (burrow occupied for 2 out of 25 survey days), the signs – digging, footprints, fresh scats - around the burrow entrance suggested a high rate of activity. This was supported by the video evidence, which showed wombat activity in the vicinity of the burrow, including digging around the burrow entrance, on all but two nights (23 / 25 nights) of the survey period.

Whether these inaccuracies in the subjective assessment of a burrow's active status constitutes a problem depends upon the context. Certainly, at the local scale, if research effort is spent on a burrow which is not active, then that effort may be wasted. Conversely, as the calculated indices of the number of wombats / active burrow are all based on subjective assessments which also includes the misidentification of the status of some burrows (Tiver 1980; Tiver 1981; McGregor and Wells 1998; Taylor 1998), we do not consider this to be a significant problem for broad area population studies. Nonetheless, consideration should be given to using small scale studies as models to develop indices prior to any broad-scale population survey, and to ensure that subjective assessments by multiple researchers are standardised to reduce potential errors in the abundance calculations.

We also noted days where no wombat activity was captured on the cameras – and hence, we did not observe a wombat entering or exiting the burrow - but we assessed that the burrow was occupied. This can be explained by the observation of a wombat entering the burrow but not emerging until several days later. We noted three instances of a wombat remaining in its burrow for more than one day, with the longest period being three and a half days (wombat entered at 05:07 on 29 November and did not emerge until 21:29 on 2 December). A second wombat also did not emerge from a different burrow for two days during the same period. This was most likely related to the weather, with our cameras recording maximum temperatures in excess of $40^{o}$ C on both 29 and 30 November 2017. A herd of feral goats was also observed grazing on the surface of the warren on the evening of the 30 November (Figure 7). This avoidance behaviour by wombats of high temperatures and outside disturbances has been previously described by multiple sources (Wells 1978; Stott 1998; Taylor 1998; Finlayson *et al.* 2003; Taggart and Temple-Smith 2008). It also highlights the merits of non-invasive approaches which reduce the potential to cause behavioural changes, and of surveys which investigate burrow occupancy rather than wombat activity, which is likely to vary seasonally and in response to environmental conditions.


*Figure 7: Feral goats examining one of our camera poles in Brookfield Conservation Park (site #1). The close-up cameras are visible in the image, which was captured on the medium-range camera. Note how the temperature at 18:30 is still 41ºC. It is likely that a combination of high temperatures and disturbance by the goats discouraged the wombat from emerging from its burrow during the nights of 29 and 30 November.*

In regard to burrow sharing by more than one wombat, whilst this is not thought to be common, it does occur, especially in areas dominated by layers of sheet calcrete limestone (Walker *et al.* 2007) where access to the subterranean shelter may be limited to breaks or fractures sites in the limestone layer. Previous studies have also suggested that these warrens can have more complex underground structures; with large open areas between the calcrete layers and several chambers which are accessed from a single burrow entrance (Swinbourne *et al.* 2016). We noted four sites (out of 18 total survey sites) where a single burrow entrance was used simultaneously by more than one wombat; Moorunde sites #4 and #5, and Dakalanta sites #2 and #3. For three out of four of these sites, burrow sharing occurred on only a few days out of the survey period. At Dakalanta site #2 burrow sharing occurred across two-thirds of the survey period (12 out of 18 days), with three wombats being observed to share the burrow for one of those days. As a consequence, we would recommend that further research be undertaken to ascertain burrow sharing behaviour and kinship relationships amongst adult wombats (Walker 2004; Walker *et al.* 2006).

With studies of this nature there is always the possibility that the cameras did not capture all the wombat activity, Although the number of cameras that we used reduces the likelihood of this occurring, we cannot discount the possibility that we may have missed one or more burrow occupancies. As a consequence, our indices of 0.43 for the Murraylands and 0.42 for the Eyre Peninsula should be considered to be minimum figures, and further research should be undertaken to verify these findings.

**Conclusions**

The use of motion-activated wildlife cameras has become more prevalent over the past 20 years, but there is still a great deal that researchers can and should learn about their capabilities and limitations if they are to gain the maximum benefit from their use. Some of our results surprised us, especially when we observed wombat activity on one camera but saw nothing on another camera that had the same focal area covered. We therefore recommend that pre-survey trials be undertaken before using cameras in the field to ensure their capabilities and limitations are fully understood, and camera settings, siting and alignment to the target are optimised. The use of multiple cameras with different positions and alignments should also be considered to overcome any potential limitations inherent in a single camera design. For surveys involving fossorial species we recommend that cameras be oriented at an angle to, rather looking directly into, the burrow.

We found that it was much easier to determine wombat behaviour and burrow occupancy rates from video than still imagery, and we recommend the greater use of video for studies of this nature.

The index of wombats / active burrow that we calculated (0.43) for the Murraylands was identical to previous studies for the region, whilst the index calculated for the Eyre Peninsula (0.42) was virtually identical. This suggests that these figures are probably robust enough for most broad-scale wombat population studies. However, we recommend that on-going studies of this nature be undertaken to refine our understanding of southern hairy-nosed wombat burrow occupation rates at different spatial scales and under different environmental conditions.

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**Conflicts of Interest**

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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# Statement of Authorship

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| Name of Principal Author (Candidate) | Michael Swinbourne | | |
| Contribution to the Paper | Identification of research gap, conceptualisation, study design, research and data collection, analysis, drafting of manuscript, submission and revision | | |
| Overall percentage (%) | 80% | | |
| Certification: | This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper. | | |
| Signature | | Date | 7 November 2018 |

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By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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# Chapter 8: The species-wide distribution and abundance of southern hairy-nosed wombats (*Lasiorhinus latifrons*)


## Abstract

*There is disagreement within the community regarding whether the distribution and abundance of southern hairy-nosed wombats (Lasiorhinus latifrons) is increasing or decreasing. On one hand, farmers and graziers within areas where wombats can be found have consistently claimed that their numbers have increased in recent decades. Conversely, conservation groups, including the International Union for the Conservation of Nature (IUCN) claim that the wombat population is experiencing a species-wide decline, and recently upgraded its conservation status to 'Near Threatened'. To resolve this disparity, we used a combination of field surveys and the analysis of satellite imagery to map the species-wide distribution, and estimate the overall population abundance, of southern hairy-nosed wombats. We found that wombat numbers have grown substantially since the last major surveys in the 1980s; however, the population growth has not been uniform. While the largest groups on the Nullarbor Plain and Gawler Ranges have experienced marked population growth, there has been only relatively modest growth in the Murraylands. On the Yorke Peninsula, while the overall population numbers do not appear to have changed, some colonies have disappeared entirely. We also found a substantial population of wombats in Western Australia which had not been previously reported.*


## Introduction

Southern hairy-nosed wombats (*Lasiorhinus latifrons*) are large fossorial and nocturnal marsupial herbivores which inhabit the arid and semi-arid regions of southern Australia. Wombats were well known to the indigenous people of the country (Miller 2005), and were first noticed by Europeans when they arrived in South Australia in the 1830s (Swinbourne *et al.* 2017). However, no attempts were made to map their species-wide distribution or to estimate their abundance until the 1970s (Aitken 1971; Aitken 1973; St.John and Saunders 1989). Unfortunately, by that time the hairy-nosed wombat population had been decimated by competition from introduced herbivores - especially rabbits - land-use changes for agriculture, and persecution by an expanding human population. Consequently, the distribution as mapped at the time was highly fragmented and smaller than it was at the time of European settlement (Swinbourne *et al.* 2017).

Six main sub-population groups were mapped during these initial surveys: the Murraylands, Yorke Peninsula, Eyre Peninsula, two population groups in the Gawler Ranges, and the Far West Coast / Nullarbor Plain region of South Australia. Scattered colonies were also thought to extend into Western Australia, but these were believed to be in low numbers only (Aitken 1973) (Figure 1). In the 1990s, two small colonies were also reported to exist in the south-western corner of New South Wales (Adam 1997).

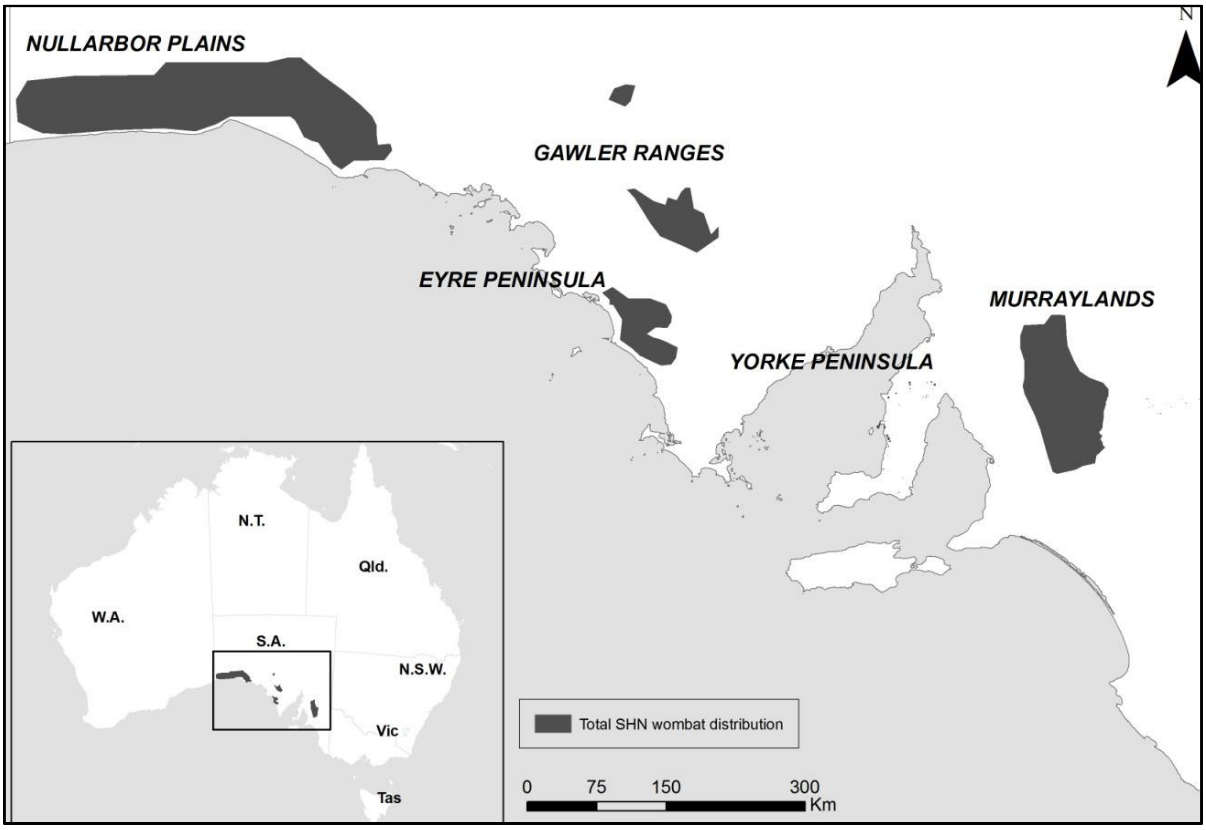


*Figure 1: Assessed distribution of southern hairy-nosed wombats in the 1980s (Ostendorf et al. 2009).*

Since the 1980s, the sub-population groups which are closest to civilisation (Murraylands, Yorke Peninsula) have been the subject of a number of studies which have examined population dynamics and trends (McGregor and Wells 1998; Ostendorf *et al.* 2009; Sparrow 2010). Unfortunately, there have been no follow-on studies of the more remote groups, and until recently there were no attempts to determine the extent of the wombat population in Western Australia (Swinbourne *et. al.* submitted manuscript).

Despite this lack of knowledge, the International Union for the Conservation of Nature (IUCN) recently upgraded the listing for southern hairy-nosed wombats from 'Least Concern' to 'Near Threatened'(Woinarski and Burbidge 2016). In making their assessment, the IUCN stated:

> *"The southern hairy-nosed wombat has declined historically in population size, number of subpopulations and area of occupancy. Many subpopulations are now isolated and may be non-viable. It faces a wide range of threats. There is limited information on population trends (particularly for the largest subpopulations, in the Nullarbor area), but estimates for some subpopulations (e.g. of 70% decline in the Murray Lands, South Australia from 2002 to 2008) suggest that it may approach an overall population decline threshold of 30% over three generations (27-36 years), currently and in the future. Hence it is listed as Near Threatened as it almost qualifies for a threatened listing under criterion A2b."*

This statement is, in some ways, contradictory. Although the IUCN concluded that the population was in decline, there was an acknowledgement that there was limited information on population trends for the largest population groups. Despite this admission, the conservation status was changed based largely on data from a single unpublished study (D. Taggart pers. comm.) in a limited area which, because of anthropogenic and other factors (Ruykys *et al.* 2009; Death *et al.* 2011; Keppel *et al.* 2015), may not be representative of the population as a whole. In contrast to this assessment, landholders in, and adjacent to, areas where wombats can be found have consistently claimed that wombat numbers have been increasing over the past few decades (Sparrow *et al.* 2011; Sparrow 2013).

Consequently, there is a clear need to rectify the deficiencies in our understanding of the distribution and abundance of southern hairy-nosed wombats in order to determine whether the population is increasing or declining, and what its true conservation status might be. To achieve this, we used a combination of field surveys and high-resolution satellite imagery (Swinbourne *et al.* 2018b) to map the species-wide distribution of southern hairy-nosed wombat and to estimate their overall abundance.

## Method

Using the methodology described in Swinbourne *et. al.* (2017), we used ArcMap (Version 10) to overlay grids consisting of 1 $km^2$ squares over satellite imagery of each of the regions where southern hairy-nosed wombats can be found; except for the Yorke Peninsula and New South Wales.

Lines of cells oriented north-south and east-west at five-kilometre intervals were selected from each grid and inspected for the presence of wombat warrens. The cells containing wombat warrens which were closest to the edge of the grid were identified and used to construct an outline of the wombat distribution in each region.

Using the ArcMap Sampling Design tool, we randomly selected 1,000 x 1 $km^2$ grid cells in each outlined region for further analysis (confidence level = 95%, margin of error = 3%) (Figure 2). For each selected cell the date of the imagery was recorded, the presence or absence of warrens was noted, all warrens were counted, and their diameter measured.

The raw warren counts from the satellite imagery were adjusted using the indices in Swinbourne *et al* (2018), and the adjusted warren counts were then multiplied by the mean number of active burrows for each warren size class, to provide a total number of active burrows for each grid cell. The active burrow data from all 1,000 randomly selected grid cells was then extrapolated by the total number of grid cells in the outline distribution to provide an overall figure of the number of active burrows for each region. For each region, several field surveys were undertaken to ground-truth the satellite data; as per Swinbourne *et al* (2018).

To calculate total wombat abundance, we multiplied the total number of active burrows by indices of 0.32 (Taggart *et al.* 2012), 0.43 (McGregor and Wells 1998), 0.5 (St.John 1998) and 0.63 (Tiver 1980) wombats / active burrow to provide an estimated minimum, median, trend, and maximum number of wombats for each region.

Because of small size of the Yorke Peninsula and New South Wales populations, the methodology described above was not appropriate for these regions. Instead, the wombat distribution and abundance in these regions were estimated by using a combination of field surveys and the analysis of satellite imagery of the locations of known and suspected population groups.

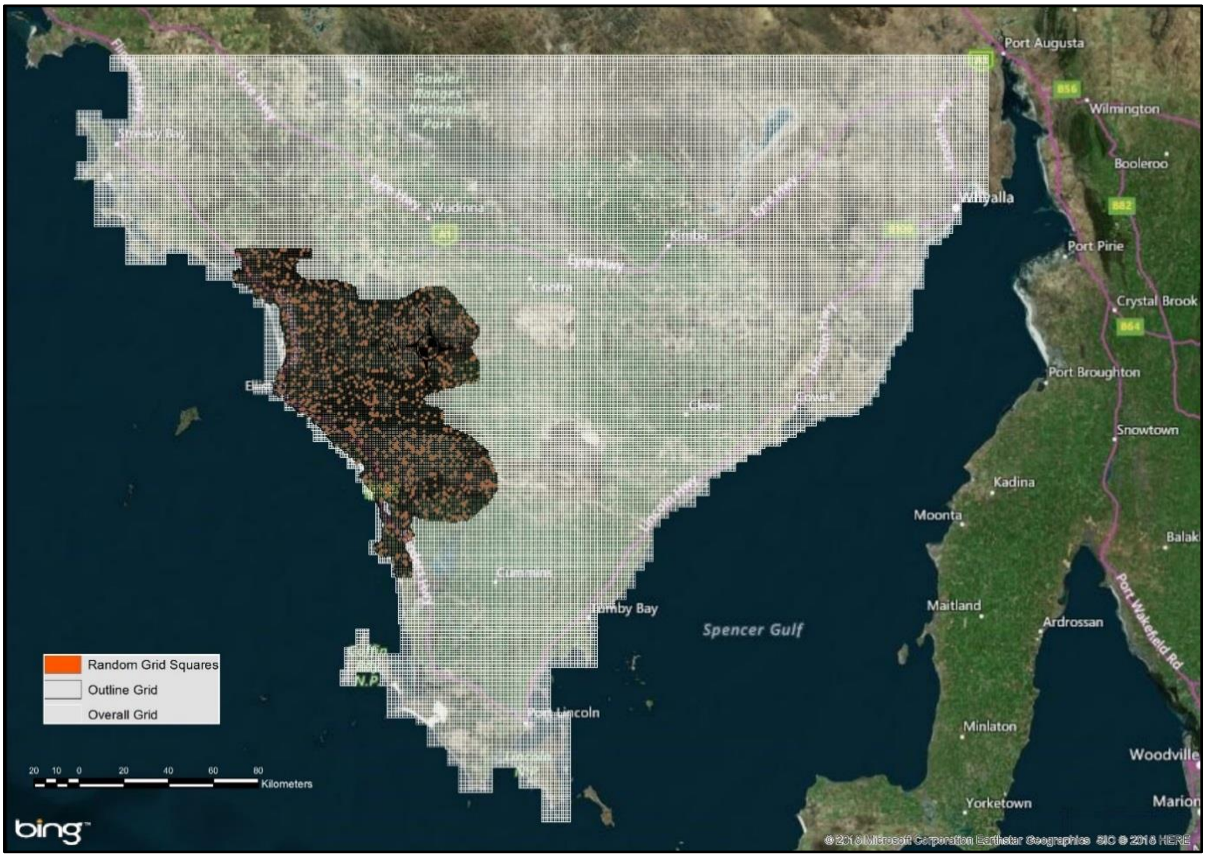


*Figure 2: Satellite image of the Eyre Peninsula showing an example of the analysis methodology used. An overlay of 1 km$^2$ grid squares was placed over satellite imagery of the region (white squares). An outline of the wombat distribution was then constructed (black squares), from which 1,000 grid 1 km$^2$ grid squares were randomly selected for detailed analysis (red squares).*

## Results and Discussion

### *Western Australia*

The distribution of southern hairy-nosed wombats in Western Australia extends from the South Australian border westwards to around Caiguna, a distance of ~ 350 km, and from the Eyre Highway northwards for ~ 75 km. The distribution is highly patchy, with the most densely populated area in the south-east near the South Australian border. In general, the population density decreases northwards and westwards, although there are isolated pockets of relatively high abundance in these areas, such as near the western edge of the region along the boundary between Rawlinna and Arubiddy stations (Figure 3). There is a small isolated colony located ~ 5 km south-east of the railway town of Forrest, which is separated from the main population group by ~ 30 km.

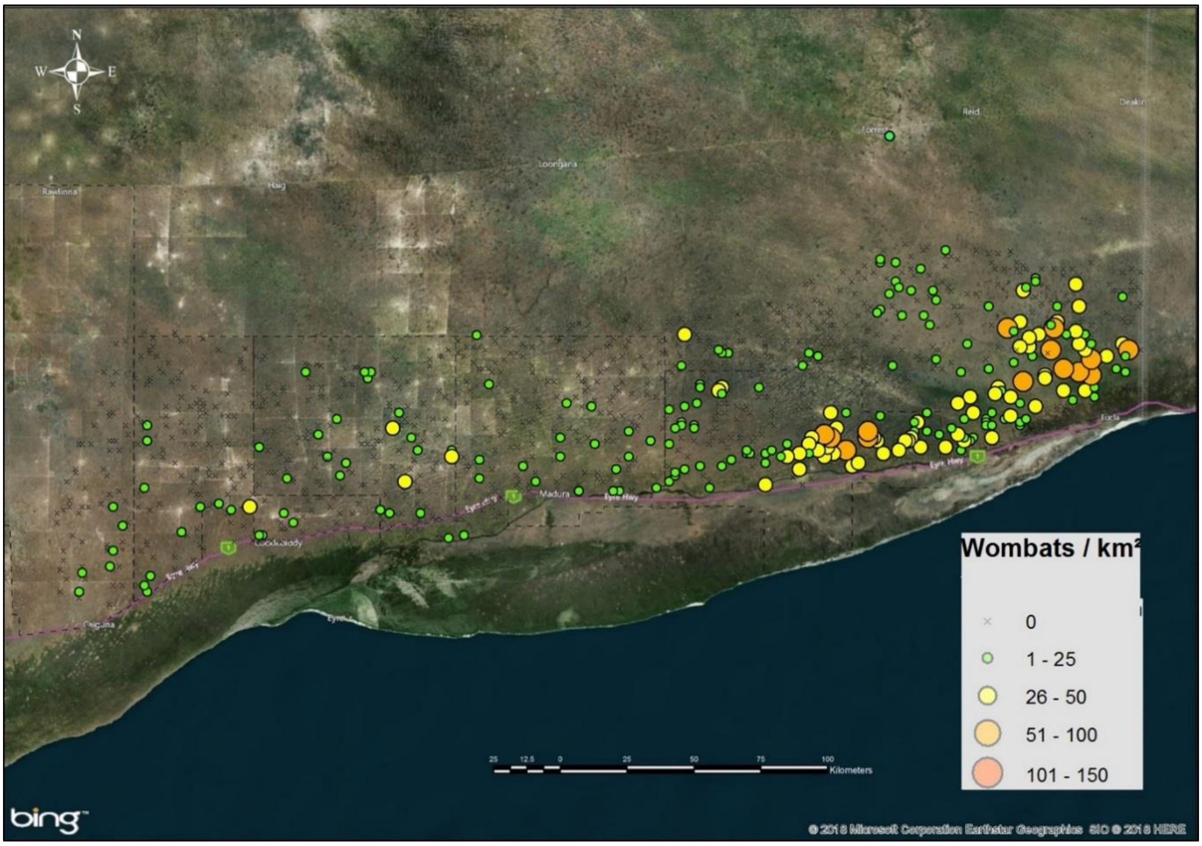


*Figure 3: Distribution and local area abundance of southern hairy-nosed wombats in Western Australia.*

Virtually all of the wombat population is located to the north of the Eyre Highway, except for a colony mid-way between Cocklebiddy and Madura. Until the turn of the 21st century, wombats could also not be found in the area below the escarpment between the border and Madura, but have recently appeared in the area between the Mundrabilla Station homestead and Mundrabilla roadhouse (B. Campbell, Mundrabilla station, pers. comm.).

The patchy nature of the wombat distribution in Western Australia appears to be a result of topography. Much of the Nullarbor consists of a mosaic of small catchments, each draining to a depression which has undergone colluvial in-filling to form a clay-pan up to one kilometre wide (Mitchell *et al.* 1979). These depressions are strong predictors for warren locations, with warrens often being concentrated around the edges of the claypan. The distribution also appears to be affected by the vermin-proof fencing constructed around the boundaries of some properties, with the western-edge of the distribution appearing to be constrained by the boundary fence between Arubiddy and Rawlinna stations.

The estimated population abundance in Western Australia is between 65,435 – 136,794, with a median estimate of 90,648 (Table 1). The mean warren density in the populated areas is 23.67 warrens / $km^2$ ($\sigma = 18.57$) (low), with a maximum warren density of 96 warrens / $km^2$ (high) in the area ~ 15 km north-west of Eucla. Whether this estimated abundance represents a declining, stable or increasing population cannot be determined, as there are no earlier surveys for comparative purposes. During our field surveys landholders in the region claimed that the wombat numbers are increasing, the distribution is expanding both northwards and westwards, and that wombats are appearing in locations where they have not been seen in living memory (B. Campbell pers. comm.).

*Nullarbor Plains (South Australia)*

The most abundant and most geographically extensive population of southern hairy-nosed wombats can be found on the Nullarbor Plain region of South Australia, from the Western Australia border east to Penong; a distance of ~ 380 km. In general, the distribution extends from the coast northwards for ~ 100 km to the transcontinental railway line, although this varies from location to location. At the western end, the north-south extent of the population is only ~ 50 km wide, while in the east it is up to 120 km wide (Figure 4).

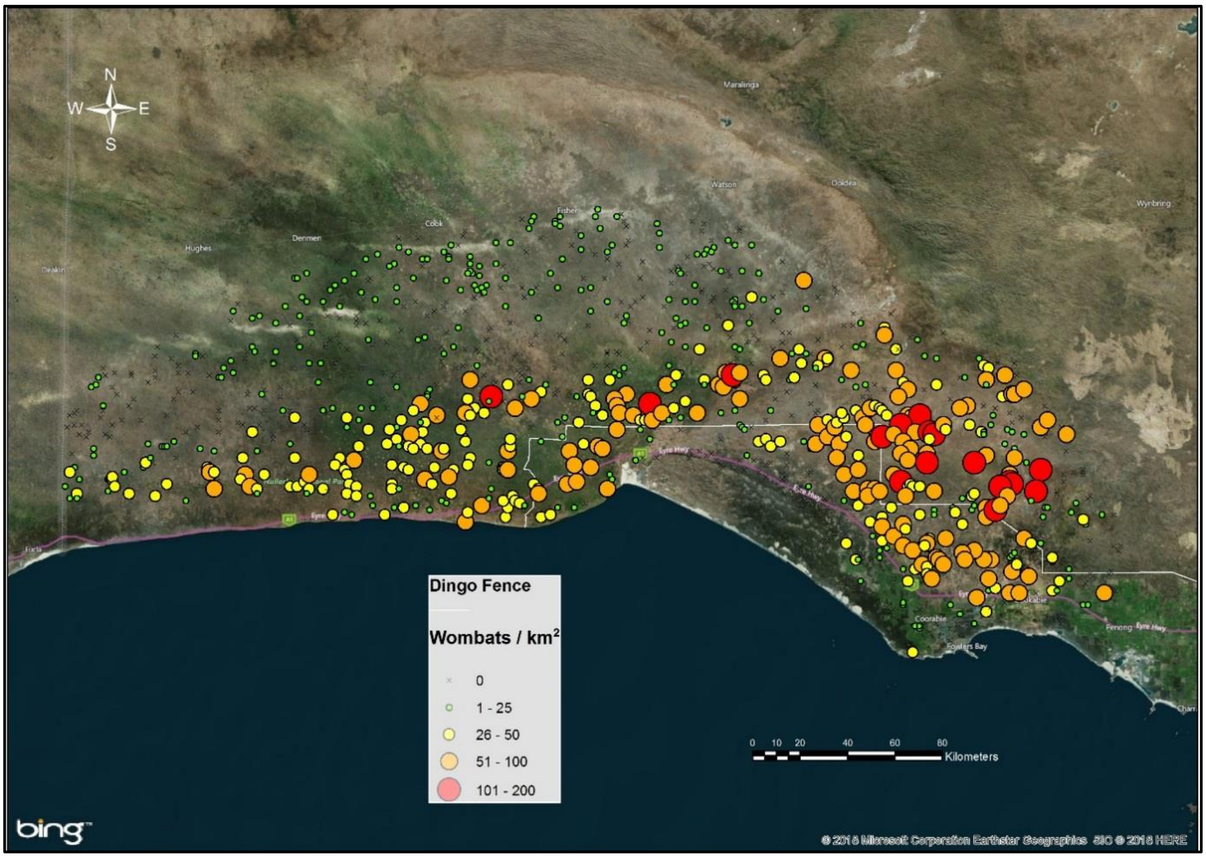


*Figure 4: Map showing the distribution and local area abundance of southern hairy-nosed wombats on the Nullarbor Plain region of South Australia.*

The population density is highest in the east and south of the distribution and decreases northwards. Despite this, there are areas within these densely populated regions which contain few or no wombats, such as in the mallee scrublands along the coast near the Yalata Aboriginal Community (Figure 4). The population density in some parts of the Nullarbor is the highest that can be found across the whole species-wide distribution, with densities exceeding 150 wombats / km$^2$ in some areas (Figure 5).

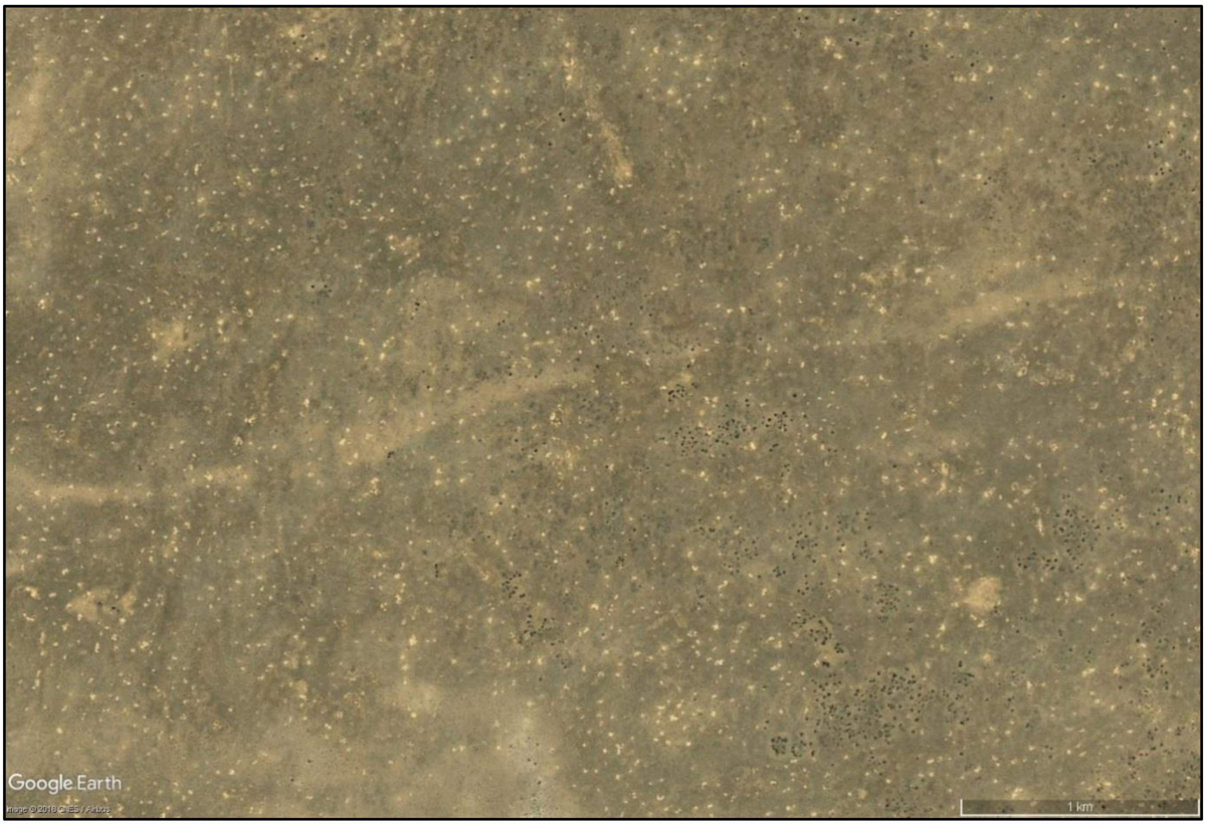


*Figure 5: Satellite image of the region ~ 50 km to the north-east of the Yalata Aboriginal Community, showing the high density of the wombat population in the area. Each white dot in the image is a wombat warren, with population densities exceeding 150 / km$^2$ (source: Google Earth 7.3.2.5487, -31.260527 132.262171, CNES / Airbus composite image, accessed 7 September 2018).*

The eastern edge of the Nullarbor population group is spatially separated from the Eyre Peninsula and Gawler Ranges populations by unfavourable landscapes. To the north-east between the Nullarbor and Gawler Ranges populations is a series of vegetated sand-dunes within the Yellabinna Regional Reserve and the Yumbarra and Pureba Conservation Parks (Figure 6). The soil within this area is too sandy for stable warren construction and wombats are completely absent; although they are in high abundance on both sides right up to the edge of the dune fields.

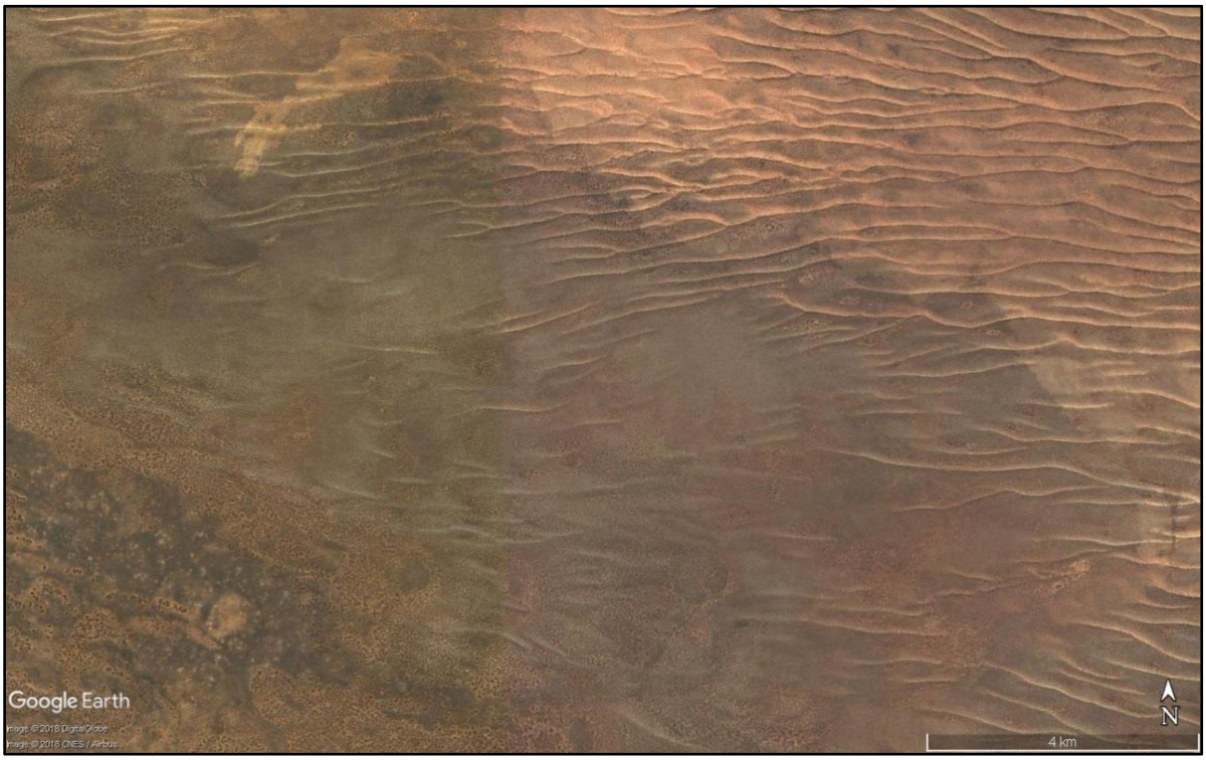


*Figure 6: Satellite image of the dune-field to the north of Penong, in the gap between the Nullarbor and Gawler Ranges populations. Note how the warren density (white dots in the bottom left corner of image) is high right up to the edge of the dunes (source: Google Earth 7.3.2.5487, -31.134011 132.736307, CNES/Airbus / DigitalGlobe composite image, accessed 13 July 2018).*

To the south-east, the landscape to the east of Penong changes from protected areas and marginal grazing lands into cropping agriculture (Figure 7). While landholders are generally tolerant of wombats on grazing land, they will take strong actions to remove any wombats from cropping paddocks (Sparrow 2013). This results in a 'wombat-free' gap of ~ 220 km between the Nullarbor Plains and Eyre Peninsula population groups – although a few isolated colonies can be found in this area in remnant bushland or in locations where they are tolerated by the landholder.

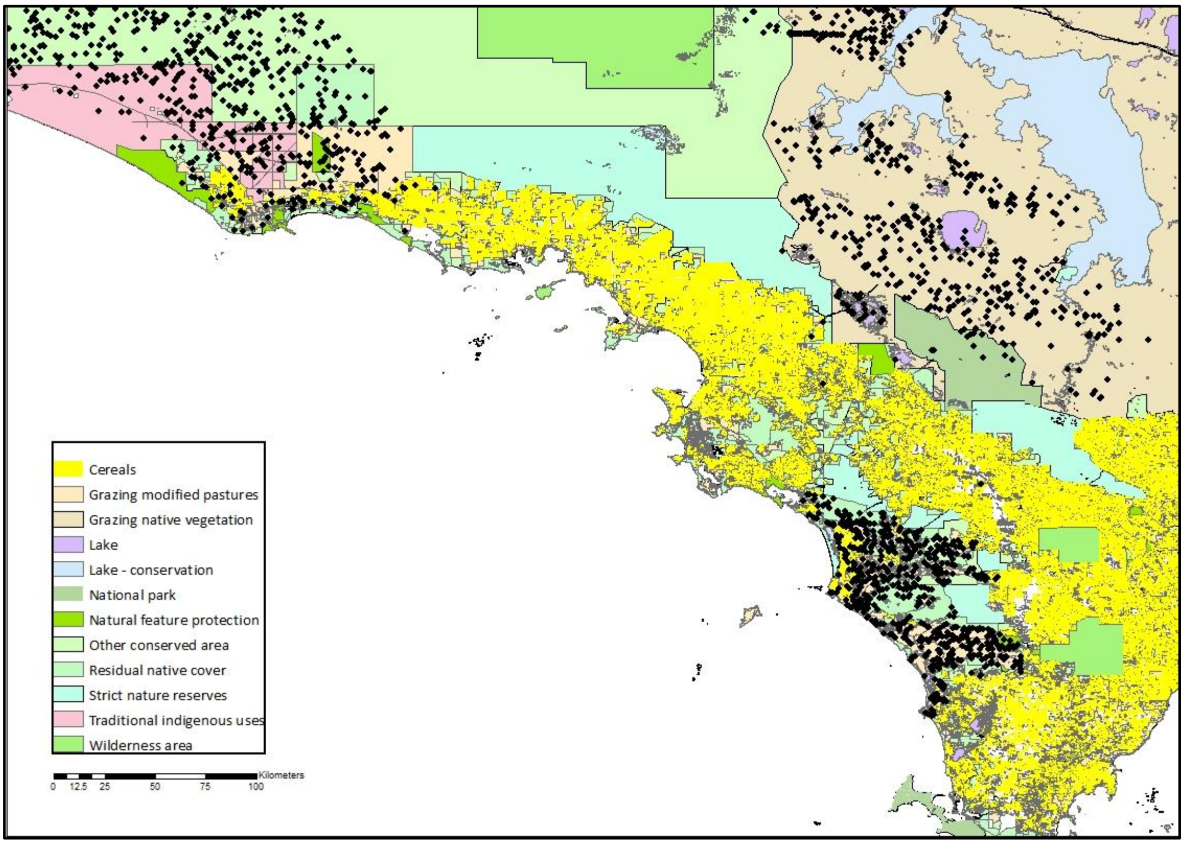


*Figure 7: Land-use map of the area between the Nullarbor Plains (black dots on left of image), Gawler Ranges (top right) and Eyre Peninsula wombat populations (bottom right). Note how wombats are absent from croplands (yellow areas), but can be found in most other land-use types, including grazing lands (light pink).*

The overall wombat population abundance of the Nullarbor Plain group is between 672,316 – 1,405,495, with a median estimate of 931,365. Previous population estimates for the region were divided into areas outside and inside the dog fence, which cuts across the south-eastern corner of the region (Figure 4). In the 1980s the estimated population outside the dog fence was 109,051, plus 162,854 inside the fence, giving an overall estimate of 271,905. In contrast, two estimates of wombat abundance inside the dog fence only were undertaken in 1995 and 2002 which estimated the population at 457,000 and 476,100 respectively (Biggs *et al.* 2002).

Comparing our population estimate with these previous estimates highlights some significant differences in the calculations of wombat abundance. The estimates from the 1980s suggest that there were more wombats inside the dog fence than outside, despite the area outside being substantially larger. It has been claimed that the numbers of wombats / active burrow may be lower outside the dog fence due to the effects of dingo predation and associated wariness by wombats; with indices as low as 0.1 – 0.2 mooted (Sparrow *et al.* 2011). However, this cannot explain the differences between the population estimates from the 1980s, as all estimates at the time were based on a common index of 0.5 wombats / active burrow (St.John and Saunders 1989). This means that the only plausible explanation for the differences in population estimates is that the overall number of active burrows calculated for the area outside the fence was lower than the number inside.

One possible explanation for this is that, while the geographic area of the Nullarbor outside the dog fence is larger than it is inside, the original surveys of wombats in the region suggested that the western edge of the distribution did not extend very far north or as far as the Western Australia border, but terminated just to the west of Koonalda homestead, ~ 70 km to the east of the border (Aitken 1973; Tiver 1980) (Figure 8). Given that we found that the wombat population now extends well beyond this terminus (Figure 9), including to the border and beyond, then either these earlier maps were inaccurate, or there has been a substantial expansion in the wombat distribution in the area outside the dog fence over the past 30 – 40 years. Notwithstanding which of these alternatives is correct, both provide support for an upwards revision in the numbers of wombats in the region.

If, as appears likely, there has been a substantial expansion in the wombat population on the western Nullarbor outside the dog fence, it would suggest that dingoes do not represent a significant threat to the wombat population, either because dingo numbers are currently too low or because they are not major predators of southern hairy-nosed wombats. In either case, more research is recommended in order to establish the relationship between the two species. Interestingly, the spatial distribution of population density as mapped in the 1970s / 80s (Figure 8) largely agrees with what we found in our surveys (Figure 4), and both assessments place the highest population densities in areas outside the dog fence. As a consequence, given that this area is both geographically larger and contains higher population densities, it is difficult to reconcile the findings which suggest there are more wombats inside than outside the dog fence.

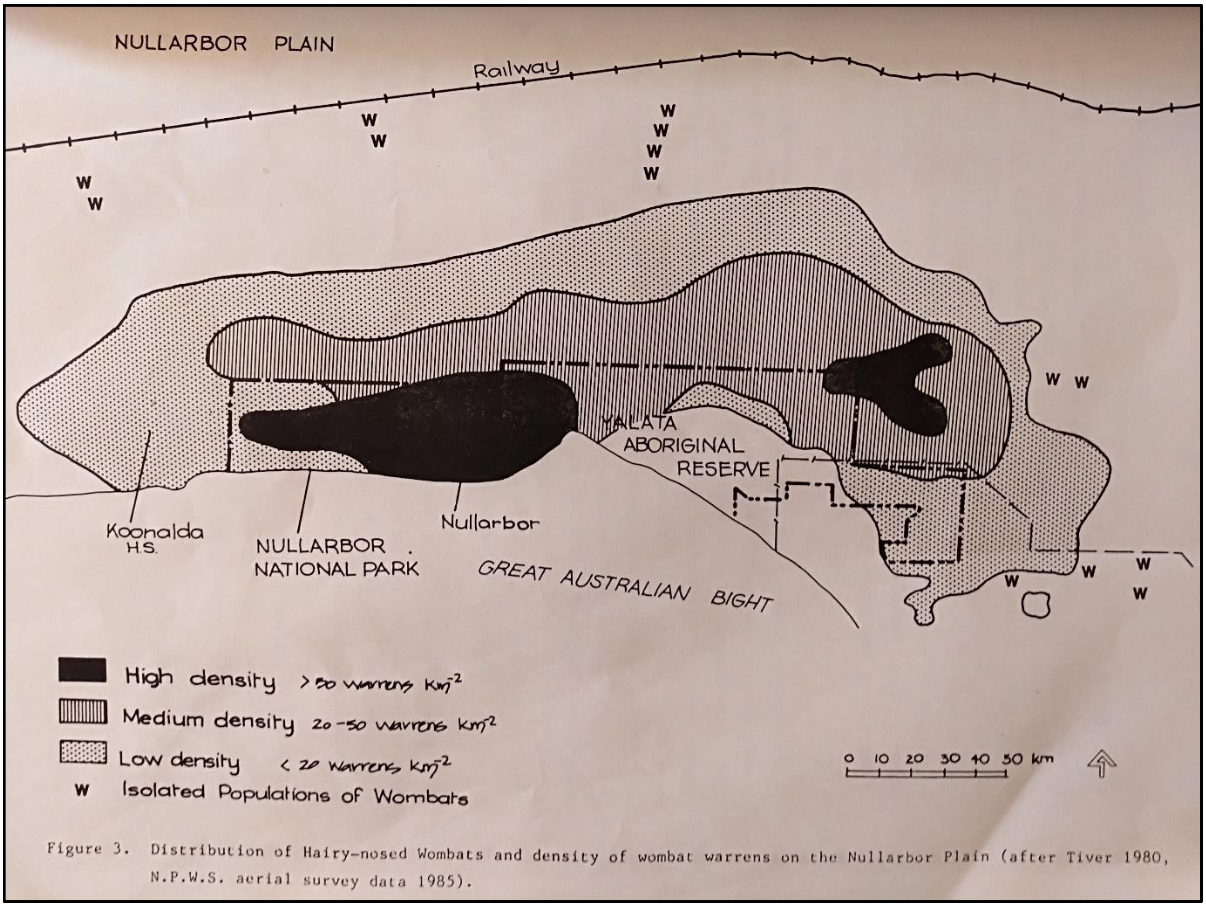


*Figure 8: Assessed distribution and abundance of southern hairy-nosed wombats on the Nullarbor Plain as mapped in the 1970s and 80s. Note how the western edge of the distribution terminates just to the west of Koonalda homestead, which is ~ 80 km from the Western Australia border (as published in (St.John and Saunders 1989)).*

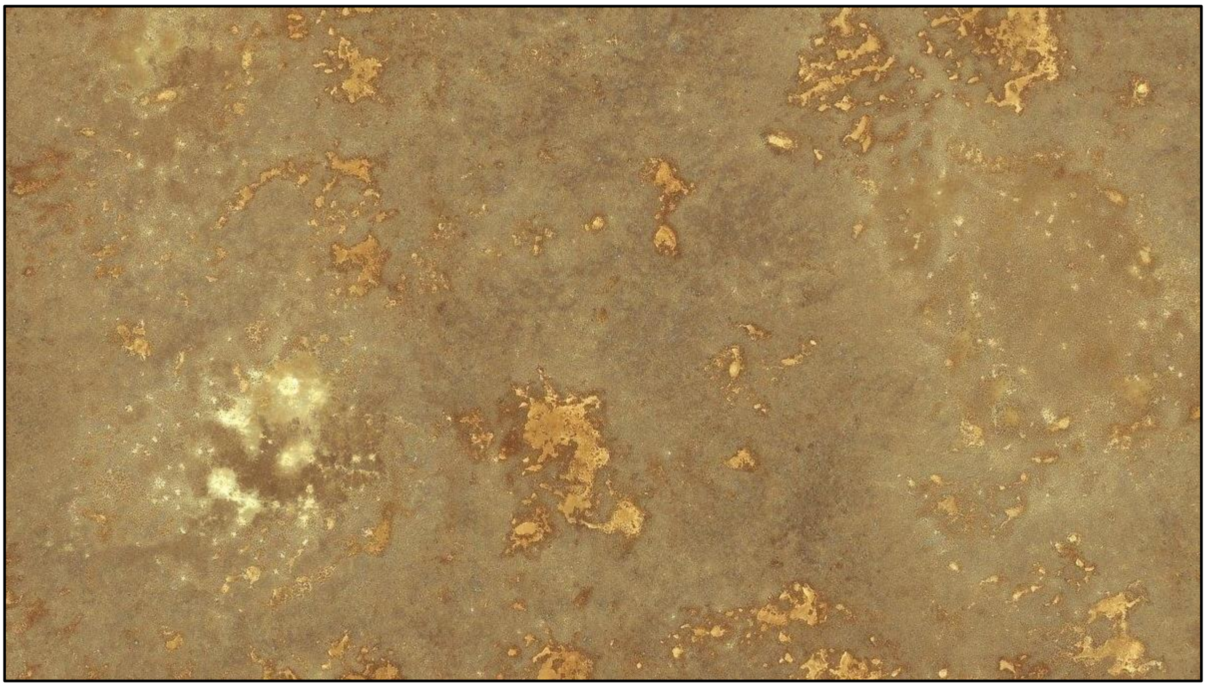

*Figure 9: Satellite image of several large colonies of wombat warrens, ~ 10 km on the South Australian side of the Western Australia border. This is ~ 50 km further west than the western edge of the distribution of wombats in South Australia as mapped in the 1970s and 80s (Aitken 1973; Tiver 1980). Wombats can now be found in large numbers right up to, and across, the border into Western Australia (source: Bing Maps on-line, -31.394899 129.14473, DigitalGlobe image, accessed 23 September 2018).*

*Gawler Ranges / Lake Harris*

The southern hairy-nosed wombat population in the Gawler Ranges / Lake Harris region occupies the most geographically and climatologically diverse region of all the wombat population groups. We found wombats on sand islands in the Lockes Claypans in the south where the mean annual rainfall is 375 mm / annum, through the valleys between the granite ridges of the Gawler Ranges, and northwards for up to 20 km north of the transcontinental railway line where wombats occur on arid plains where the mean annual temperature is more than 3$^{o}$ C higher and annual rainfall is less than half of what it is in the south of the region. The overall geographic extent of the population group is ~ 240 km N-S by 120 km E-W (Figure 10).

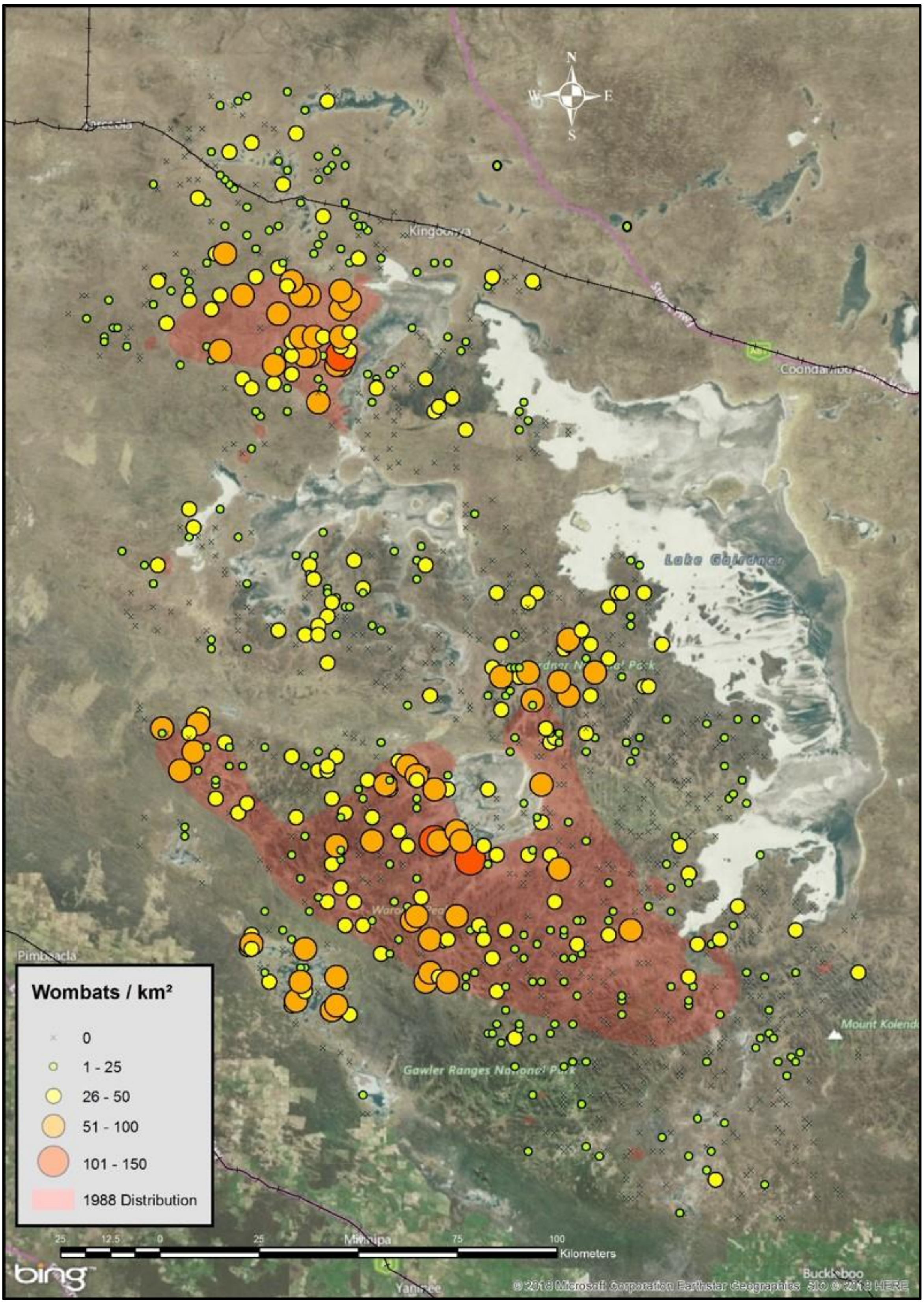


*Figure 10: Map showing the distribution and local area abundance of southern hairy-nosed wombats in the Gawler ranges region. Note the significant expansion in distribution since the previous surveys in 1988.*

The most densely populated areas are close to both Lake Acraman and Lake Harris, although wombats occur in high population densities (51 – 100 / $km^2$) throughout many parts of the region, including in areas from which they were previously reported as being absent. We assess the total number of wombats in the region is between 149,051 – 311,595, with a median estimate of 206,482 (Swinbourne *et al.* 2018a).

The findings from our survey suggests that there has been a marked increase in both distribution and abundance in the region since the 1980s when the most recent broad area survey of the region was completed (St.John and Saunders 1989). At that time two sub-population groups were discovered; a group centred to the south and west of Lake Acraman, around the Gawler Ranges themselves; and a small group in the catchment area to the west of Lake Harris (Figure 10). Both of these population groups were assessed as supporting low population densities. Indeed, so few wombats were reported to be in the group to the west of Lake Harris that it was described as 'fragile', with an overall population density of just three wombats / $km^2$ (St.John 1998). In contrast, in 2016 we assessed the overall population density in this region had grown to medium (25 – 50 / $km^2$), with wombats occurring in high population densities (50 – 100 / $km^2$) in the core area immediately to the west of Lake Harris. We also found wombats well beyond the limits of the 1988 distribution, including up to 20 km to the north of the transcontinental railway line (Figure 11).

Even in the south of the region around Lake Acraman, the overall population density in the 1980s was assessed as 'low' (< 20 / $km^2$). This was despite there having been a sustained increase in both distribution and abundance in this group since the 1960s (St.John and Saunders 1989) when wombats were described as 'inconspicuous' in many parts of the region (Aitken 1971). In 2016, we assessed the population density on Hiltaba Station in the populated areas (wombats are not present on the granite ridges of the Gawler Ranges) as between 50 – 100 warrens / $km^2$ (Figure 12).

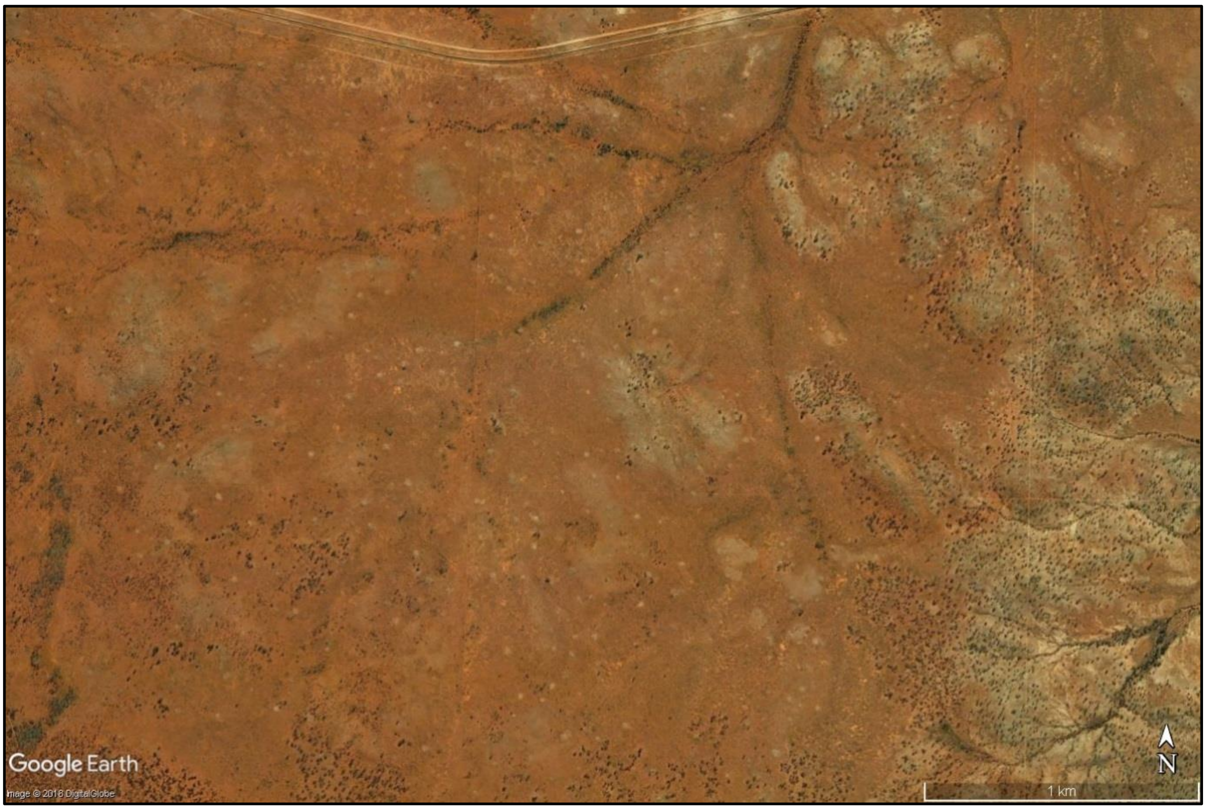


*Figure 11: Large number of wombat warrens (white dots on image), on the edge of the transcontinental railway line (line in top centre of image), mid-way between Kingoonya and Tarcoola. This is ~ 20 km north of the distribution which was mapped in the 1980s. Although surveys in the 1970s and 80s reported no wombats in this area, in 2016 we found warren densities of between 50 – 100 / km$^2$ (source: Google Earth 7.3.2.5491, -30.869495 134.942707, DigitalGlobe image, accessed 15 September 2018).*


*Figure 12: Hiltaba Station, in the southern Gawler Ranges. In the 1970s, wombats were described as 'inconspicuous' in the area. In 2016 the population density in the vicinity of the homestead was assessed as ~ 100 warrens / km$^2$ (source: Google Earth 7.3.2.5491, -32.149954 135.076895, CNES/Airbus image, accessed 15 September 2018).*

*Eyre Peninsula*

The wombat population on the Eyre Peninsula lies on the west coast of the peninsula between the towns of Port Kenny and Mount Hope, and is surrounded by the Kulliparu, Cocata, Barwell, Bascombe Well, Peachna, and Shannon Conservation Parks (Figure 13). The population has expanded and consolidated since the 1970s, especially in the southern areas of the region between Sheringa and Mount Hope where the local area distribution was previously considered to be patchy (Aitken 1971). Wombats have also infilled the area around Mount Wedge (Figure 14) from where they were thought to be absent in the 1980s (St.John and Saunders 1989) and moving into the agricultural lands closer to the coast (Figure 15).

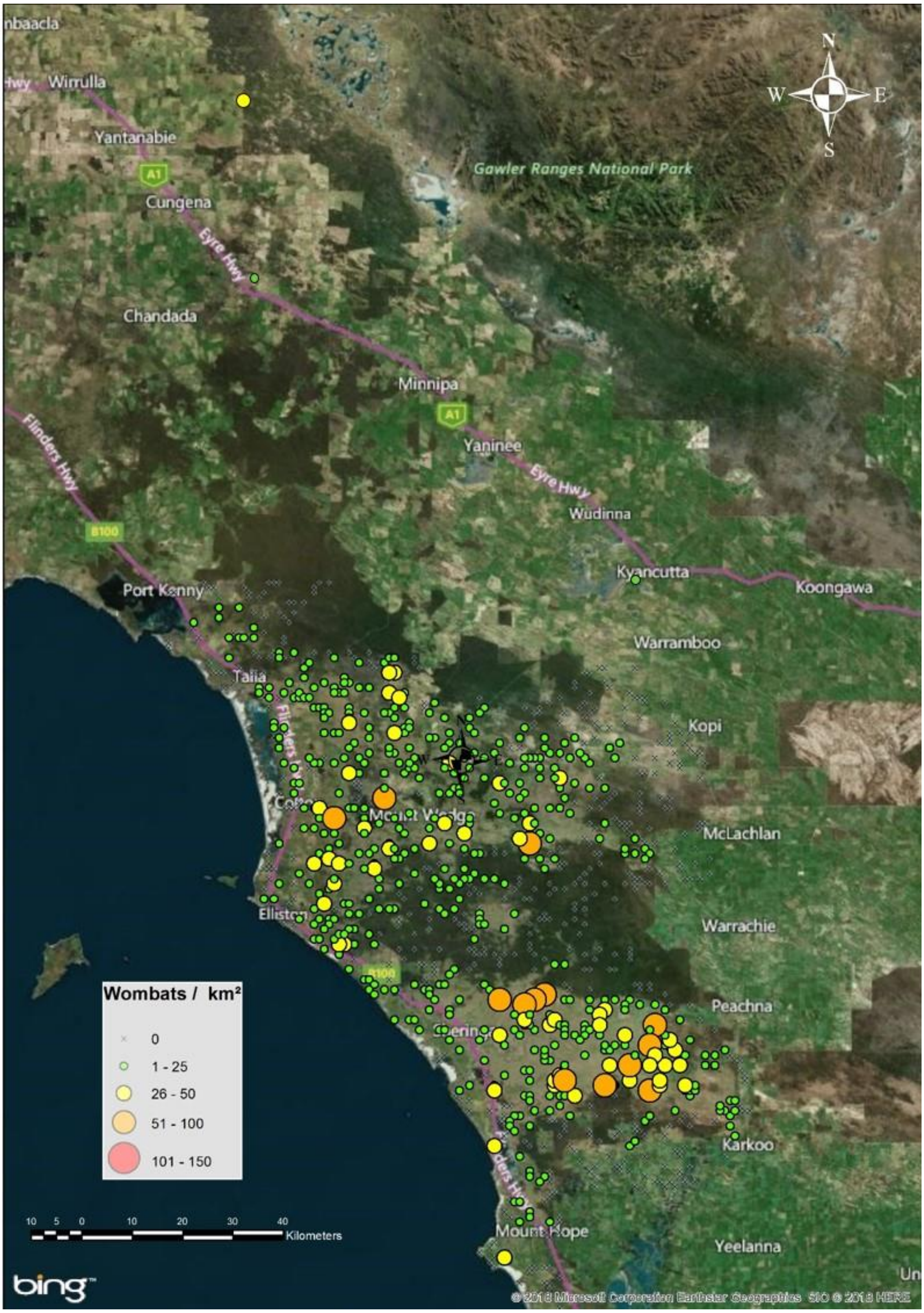


*Figure 13: Map showing the distribution and abundance of southern hairy-nosed wombats on the Eyre Peninsula. The population is mostly limited to grazing lands (light brown), and it is surrounded by dense vegetation (dark green) and croplands (bright green). Note the isolated colonies near Kyancutta, Poochera (north-east of Chandada) and Yantanabie.*


*Figure 14: Satellite images from 2005 (left), 2013 (centre) and 2015 (right) of agricultural land on the edge of scrubland near Mount Wedge, showing wombat warrens encroaching onto farmland (source: Google Earth 7.3.2.5487. DigitalGlobe composite image, -33.445813 135.116615, accessed 5 September 2018).*


*Figure 15: Satellite images from 2010 (left) and 2017 (right) of the area ~ 5 km south-east of Elliston showing the recent growth in the wombat population in the region (source: Google Earth 7.3.2.5487. DigitalGlobe composite image, -33.666896 134.935819, accessed 5 September 2018).*

While there is still some scope for further expansion, the distribution appears to be close to its geographic limits in the region, as the dense mallee scrubland in the conservation parks, and the surrounding croplands, are both generally unsuitable for wombats (Aitken 1971). Despite this, there are a number of isolated colonies on farmland in the area, including near Kyancutta, Poochera and Yantanabie (Figure 16). The small size of these colonies and their reliance on the continued acceptance of their presence by the relevant landholders means that their long-term prospects are not secure.


*Figure 16: Satellite image of Kyancutta, in the centre of the Eyre Peninsula. There is a colony of southern hairy-nosed wombats located in the bushland to the west of the town (centre of the image) surrounded by croplands. The small size, geographic and genetic isolation, and reliance on the continued acceptance by the relevant landholder, means that the long-term prospects of colonies like this are not secure (source: Google Earth 7.3.2.5487. CNES / Airbus image, -33.139539 135.521314, accessed 25 September 2018).*

In addition to the expanding distribution, the abundance on the Eyre peninsula also appears to have been increasing over the past 30 years, and now numbers between 36,195 – 75,667, with a median estimate of 50,141 (Table ); up from an estimated 9,502 in 1989 (St.John and Saunders 1989).

*Yorke Peninsula*

A region-wide survey of wombats on Yorke Peninsula was undertaken in 2009 (Sparrow 2010). Twenty-five geographically dispersed colonies were located which were grouped into 48 geographic sub-colony areas, most of which contained fewer than 20 individual animals (Figure 17). The largest colonies were located near Point Pearce / Urania on the west coast of the peninsula, which were estimated to contain a combined total of 307 animals. The overall population abundance in the region was estimated to be 696.

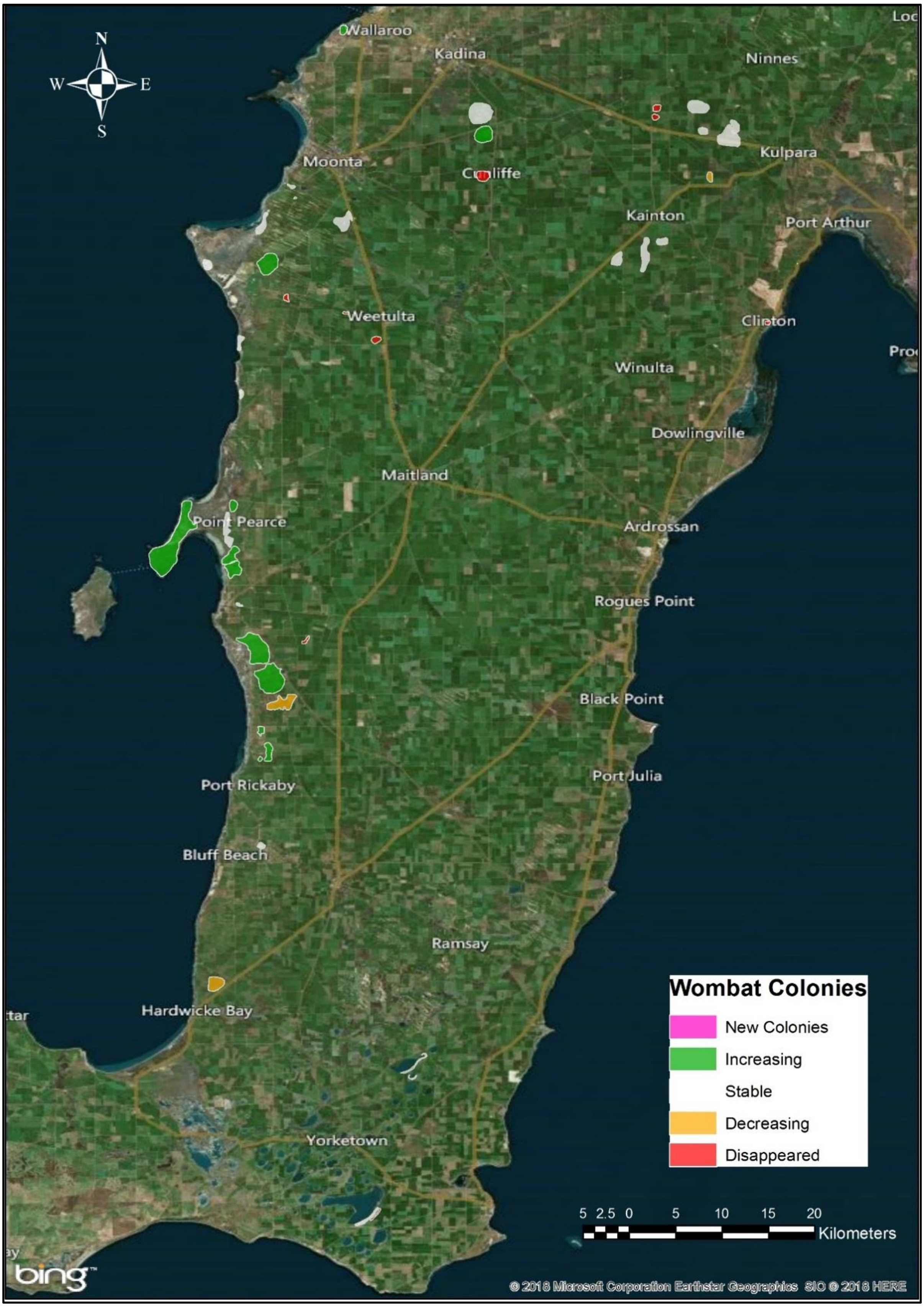


*Figure 17: Map showing the distribution of wombats on Yorke Peninsula, and the population trend since the last survey in 2009.*

Of the 48 sub-colony groups located in the original survey, we found 12 that appeared to be growing in extent and / or population density (Figure 18), with all but two of these being located along the west coast near Point Pearce / Urania. Twenty sub-colonies appeared to be stable / no noticeable change, five were declining, and eleven had disappeared completely (Figure 19). Most of the colonies which have disappeared were small colonies located in the centre of the peninsula on agricultural land, and it appears as if the landholders have removed the warrens either to control wombats, or following a natural decline in the wombat population. We also located one additional colony that was not mapped in the 2009 survey; on the north-east coast ~ 6 km north of Clinton.


*Figure 18: Satellite images from 2006 (left) and 2015 (right) of the eastern edge of the Point Pearce wombat colony showing how the population is increasing in the area, and moving out of the indigenous area onto agricultural land. (source: Google Earth 7.3.2.5487. DigitalGlobe composite image, -34.560218 137.540039, accessed 5 September 2018).*


*Figure 19: In contrast to the population growth shown in Figure 18, this colony to the north of Balgowan that was present during the survey in 2009 (2006 image at left) had disappeared by 2013 (right) (source: Google Earth 7.3.2.5487, CNES Airbus composite image, -34.201763 137.546638, accessed 4 September 2018).*

While a number of small colony groups have disappeared, the overall number of wombats on the Yorke Peninsula appears to have remained relatively constant from 2009 - 2018, with growth occurring in some of the larger colonies. The consequences of small population size and geographic isolation means that it is likely that more small colonies will disappear either due to landholder action, natural disturbance, or as a result of being unable to sustain themselves. Further, while the wombat population in the larger groups on the west coast appears to have increased in some areas, there is little scope for it to expand further, as these groups are geographically constrained by surrounding agricultural land. As a consequence, we assess that over the medium to long-term the number of wombats on the Yorke Peninsula will probably decline as each small isolated colony becomes unviable and disappears, until only the larger colonies remain; isolated by surrounding farmlands.

*Murraylands*

The distribution of wombats in the Murraylands extends from near Walkers Flat in the south to north of Burra in the mid-north of the state. Wombats only occur on the western side of the Murray River, and can be found across the river flats and into the foothills of the Mt Lofty

Ranges. The core area with the highest population density is located on the river flats between Blanchetown and Swan Reach; although there are local areas of high abundance in several other areas throughout the southern half of the region. Although the distribution extends well to the north of Morgan on the north-west bend, and up to ~ 30 km north of Burra, the population density to the north of the Morgan-Burra Rd (Goyder Hwy) is generally patchy and in much lower numbers than it is to the south (Figure 20).

The overall abundance of wombats in the Murraylands is estimated to be between 40,802 – 80,330, with a median estimate of 54,828. This figure is higher than 30,636 which was calculated for the region in 1980 (Tiver 1981) and 33,871 in 1992 (McGregor and Wells 1998), but lower than a survey undertaken in 2012 which estimated the population at 148,448 (Taggart *et al.* 2012). However, the surveys in the 1980s / 90s did not survey the entire region (omitting the area to the north of Morgan), and the 2012 estimate was thought to be very uncertain. Consequently, establishing a population trend over the intervening period is difficult. While wombats are present to the north of Morgan today, and were known to be in some areas (e.g. near Burra) at the time of the earlier surveys (Ostendorf *et al.* 2009) – but were not included in the population estimates – landholders suggest that the wombat population in the central and northern Murraylands has been increasing over the past few decades (Lindner 20018). As a consequence, even accounting for the unreliability of the population estimates, we suggest that the overall population numbers in the region today are greater than they were in the 1980s and 90s, albeit with the likelihood that fluctuations may have occurred during this period in response to climatic variables such as drought (Alpers *et al.* 1998).

This estimate of an increasing population is contrary to the conservation status of southern hairy-nosed wombats in the International Union for the Conservation of Nature (IUCN) Red List, which recently upgraded the species' status from Least Concerned to Near Threatened (Woinarski and Burbidge 2016). This was predicated on an assessment of a population decline in some sub-population groups in the Murraylands of up to 70% between 2002 – 2008. The IUCN also noted that much of the information on population numbers and trends was out-of-date, and that the assessment was based on limited data.

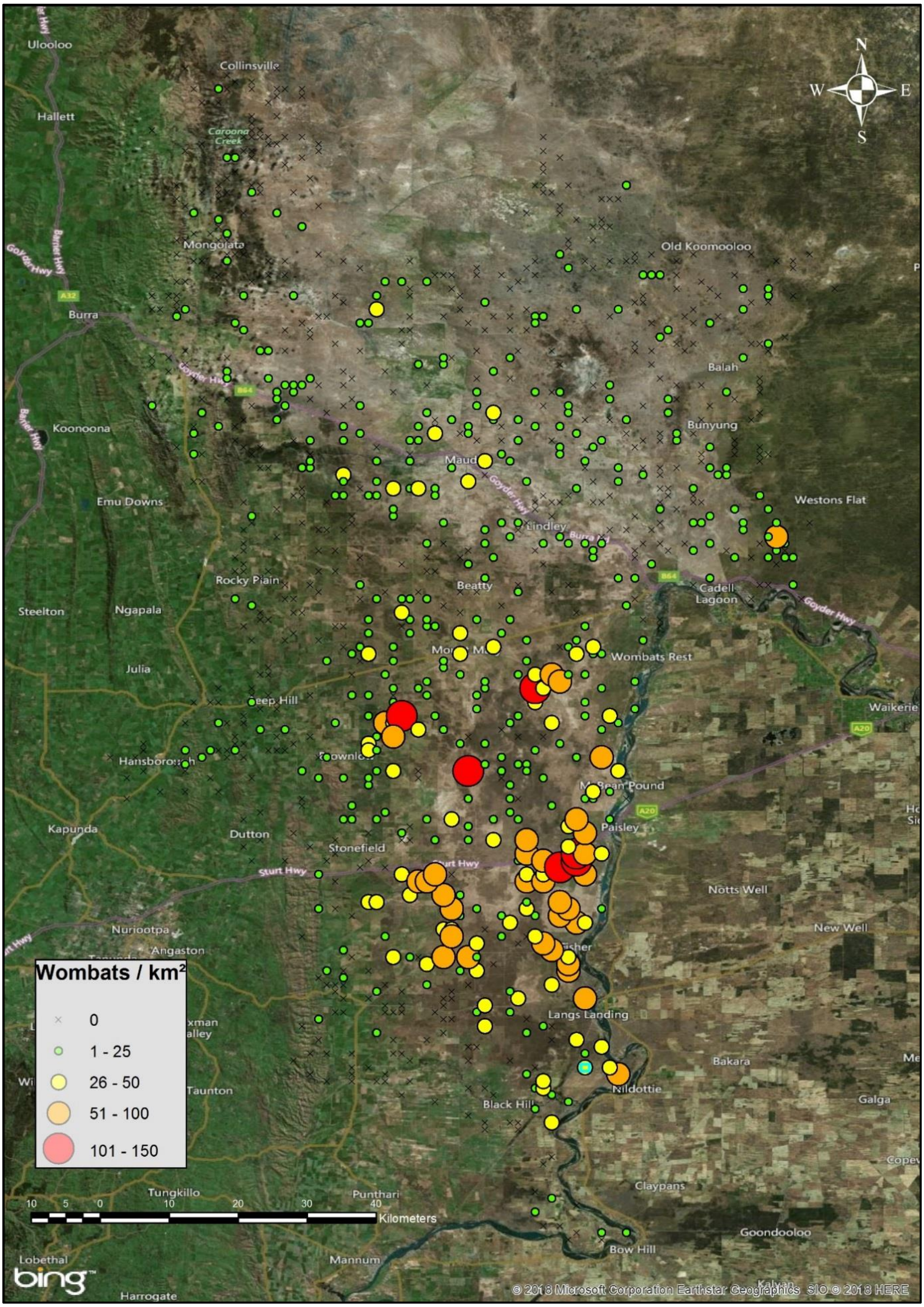


*Figure 20: Map showing the distribution and local area abundance of southern hairy-nosed wombats in the Murraylands region.*

In contrast to the study which suggested a long-term decline in parts of the region (Taggart and Robinson 2008), other long-term studies report a steady increase in numbers since the 1970s (Taylor 2018). This suggests that, while the overall wombat numbers in the Murraylands region have probably increased over the last few decades, there are likely to have been local factors which influenced population abundance at the small spatial scale, and population trends will have varied in different locations.

*New South Wales*

Two colonies of southern hairy-nosed wombats were reported along the Darling Anabranch in south-western NSW in the 1990s (Abbott 2009) (Figure 21). In July 2018 we conducted a follow-on survey to try to find evidence of their presence but could find no sign of wombats in the region. While a number of rabbit warrens were located at the sites of the earlier reports, there were no traces of any wombat inhabitation in the recent past.

While both species of hairy-nosed wombats were once relatively common in NSW (Swinbourne *et al.* 2017), there is no reliable evidence of their on-going presence.


*Figure 21: Reported locations from the 1990s of southern hairy-nosed wombats in south-western NSW. There is no reliable evidence which supports their on-going presence in the region.*

*Other Locations*

During our survey we received a number of reports of southern hairy-nosed wombats in areas well outside the main population groups – some of which were based on credible evidence such as photographs. These included:

- Ned's Corner, in the north-western corner of Victoria (ABC News 2011);
- Andamooka, mid-way between Andamooka and Roxby Downs (ABC News 2016); and
- Black Rock, mid-way between Orroroo and Peterborough in the southern Flinders Ranges (J. Manion pers. comm., 20 October 2015)

Ground and satellite imagery searches of the first two locations did not reveal any signs of the presence of wombats. Conversations with land-holders and locals strongly suggested that the most likely explanation was that the sighting was of an animal was deliberately released into the area, rather than being part of an extant colony group. A similar explanation is likely for Black Rock. Although burrows are present at that location, the landholder provided photographs of her patting the wombat, which strongly suggests that it was quite tame and was also probably a deliberate release.

*Table 1: Estimated population abundance for each region, based on a range of indices of wombats / active burrow.*

| Index | Western Australia | Nullarbor | Gawler Ranges | Eyre Peninsula | Yorke Peninsula | Murraylands | Total |
|---|---|---|---|---|---|---|---|
| 0.32 | 65,435 | 672,316 | 149,051 | 36,195 | 517 | 40,802 | 964,316<br>0.32 |
| **0.43** | **90,648** | **931,365** | **206,482** | **50,141** | **696** | **54,828** | **1,334,16<br>0.43** |
| 0.50 | 105,405 | 1,082,983 | 240,095 | 58,304 | 809 | 63,754 | 1,551,35<br>0.5 |
| 0.63 | 136,794 | 1,405,495 | 311,595 | 75,667 | 1020 | 80,330 | 2,010,90<br>0.63 |

## Conclusion

Given the incomplete nature of some of the earlier population surveys and the large variations in some of the abundance estimates - especially for the Murraylands and Nullarbor Plains - it is difficult to provide an accurate assessment of the scale of any species-wide or regional population trends. That being said, there appears to be little doubt that the species-wide distribution and abundance of southern hairy-nosed wombats has increased since the last major surveys were undertaken in the 1980s. In some regions, especially in the more remote locations such as the Gawler Ranges, the differences between the previous surveys and what we found has been substantial. We also found a large population of wombats in Western Australia which had gone unreported until our survey.

Despite this, the population trends in the different regions does not appear to have been uniform. On the Yorke Peninsula there has been no apparent change in population numbers since 2009. Further, the loss of 11 out of 48 spatial sub-colony groups is a cause for concern, and we assess that more groups are likely to disappear over the medium term, which will lead to a population decline in the region. In the Murraylands, the main population group closest to Adelaide and the best studied, the estimated increase in the overall wombat population has been relatively small, and some areas within the region have experienced population declines due to adverse local factors.

As a consequence of these variations in population trends, any policy or strategy for the management of southern hairy-nosed wombats would need to take into account all the relevant local and regional factors before determining the most appropriate course of action. This should include consideration of not only the current population trends, but how the population may change into the future as a consequence of the various local, regional, and species-wide influences.

Finally, given the overall increase in population numbers, the upgrade in the species' conservation status by the IUCN in 2016 does not appear to have been justified, and we recommend that this be reversed.

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# Statement of Authorship

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| Name of Principal Author (Candidate) | Michael Swinbourne | | |
| Contribution to the Paper | Identification of research gap, conceptualisation, study design, research and data collection, analysis, drafting of manuscript, submission and revision | | |
| Overall percentage (%) | 80% | | |
| Certification: | This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper. | | |
| Signature | | Date | 7 November 2018 |

## Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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| Contribution to the Paper | Supervision, data collection, evaluation and editing of the manuscript | | |
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# Chapter 9: Southern hairy-nosed wombats (*Lasiorhinus latifrons*): why are they 'there' but not 'there'?


## Abstract

*Southern hairy-nosed wombats inhabit a fragmented distribution across the arid and semi-arid regions of southern South Australia and the south-eastern corner of Western Australia. At the time of European settlement the distribution was more widespread and extended further east and west, with the population being mostly contiguous. At the local level the distribution and population density can be highly patchy, with large clusters of warrens in some areas but with few to no warrens being found in neighbouring areas. In order to understand the factors that determine why the wombat distribution is fragmented and patchy at different spatial scales, we mapped the species-wide distribution and correlated the location of over 8,130 data points (5,349 presence points and 2,781 absence points) with environmental and landscape data. At the species-wide scale, the wombat distribution appears to be most strongly influenced by rainfall, with no wombats being present in areas where the mean annual rainfall is < 154 mm. Local area abundance is lower in areas where rainfall is ≤ 227 mm /annum and / or the index of winter rainfall variability is > 1.18 (moderate-high). At the regional / local scale, soil clay content and vegetation class are important considerations. Wombat warrens can only be found in areas where the soil clay content is between 9 – 40% (16 – 28% preferred), and warren abundance is higher in open vegetation classes (saltbush / bluebush shrublands, grasslands) than in closed vegetation classes (mallee woodlands with shrubby understory). Over-riding all these environmental influences on the wombat distribution are anthropogenic land-use practices. Although 38% of the wombat distribution is located in protected areas and 51% is located on grazing land (rangeland grazing = 35%, modified pastures = 15% ), they are virtually absent from croplands (~ 2%).*


## Introduction

Human influences on the Australian landscape have fundamentally transformed the ecosystem. The clearing of native vegetation for agriculture, the introduction of exotic plant and animal species, the expansion of human settlement, the removal of apex predators, bringing water to areas from where it was previously absent, and the over-exploitation of some native species, have radically transformed the landscape; favouring some species and causing the decline and extinction of others. These changes are likely to be further exacerbated by an increasing human population, the ongoing removal / decline of native vegetation, an expansion in the distribution and abundance of exotic plant and animal species, over-grazing, and the influences of anthropogenic climate change. As a consequence, there is a need to better understand how these, and natural factors such as climate, vegetation and soil affect wildlife species if we are to make properly informed decisions on their management; whether that be to protect a declining population or to control an expanding one (Fryxell *et al.* 2014).

Southern hairy-nosed wombats (*Lasiorhinus latifrons*) are large (up to 38 kg), fossorial and nocturnal marsupials endemic to the arid and semi-arid regions of south-central South Australia and the south-eastern corner of Western Australia. There are five main population groups (Figure 1); the Nullarbor Plain region, Gawler Ranges / Lake Harris; Eyre Peninsula; Yorke Peninsula; and the Murraylands. The distribution extends from the southern coastline of Australia northwards for a maximum distance of ~ 220 km in the Gawler Ranges / Eyre Peninsula region, to around 100 km at the western edge near Caiguna in Western Australia. Population density also tends to be greater in the south and decreases northwards. This suggests that there may be one or more climatological or landscape factors which limit the northwards extent.

A fragmented distribution like that of the southern hairy-nosed wombat suggests that the species has either expanded its range by migrating across unfavourable landscapes to inhabit new areas of favourable habitat, and / or that the distribution was once largely contiguous but changes to the ecosystem caused some areas to become unsuitable for ongoing occupation (Levin 1974). While the wombats' fragmented distribution and abundance is thought to be driven by a range of anthropogenic and environmental factors, some of which are related to the European settlement of Australia (Swinbourne *et al.* 2017), there have been few attempts to understand the full suite of causes at different spatial scales (Löffler and Margules 1980; Ostendorf *et al.* 2009; Marshall *et al.* 2017).

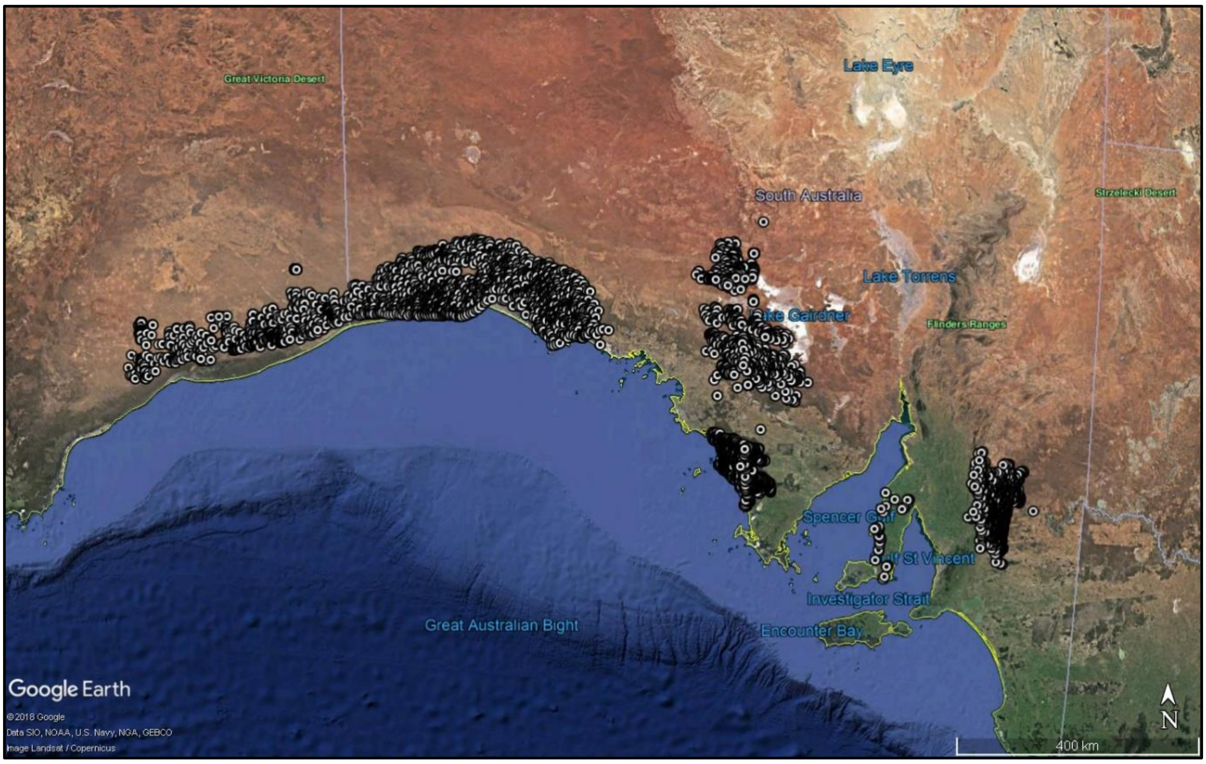


*Figure 1: Google Earth satellite image showing the species-wide distribution of southern hairy-nosed wombats. Each dot on the map represents the location of a randomly selected active warren used in the data analysis.*

In addition to having a fragmented species-wide distribution, the local area distribution and abundance of southern hairy-nosed wombats can be highly patchy. In some areas large numbers of warrens can be found within a relatively small area, while nearby locations are completely devoid of any wombats. This begs the obvious question: why can wombats be found where they are? And just as importantly, why can they not be found where they aren't? An understanding of those factors is important if we are to determine how the distribution might change in response to the ongoing influences of climate change and other changes to the ecosystem.

To achieve this, we used a combination of field surveys and high-resolution satellite imagery to map the species-wide distribution of southern hairy-nosed wombats and to estimate their overall abundance. The results were then correlated with climate and landscape data in order to understand the factors which drive the fragmentary and patchy nature of the wombat distribution.

**Method**

During the course of field surveys conducted between 2015 – 2018 across all regions where southern hairy-nosed wombats are located, and using the methodology described in Swinbourne *et. al.* (2018a), we marked the position, and measured the size and counted the number of burrows of selected wombat warrens. The warren data was then correlated with an analysis of satellite imagery (Swinbourne *et al.* 2018b) to build a database of presence and absence points with associated warren attribute information (size, # of burrows). Presence is defined as the location of an active warren randomly selected from within a 1 $km^2$ grid square, and absence is the centre of a 1 $km^2$ grid square which contains no warrens (Swinbourne *et al.* 2018a).

The collated presence / absence data were placed into a Microsoft Excel spreadsheet and uploaded onto ESRI ArcMap (version 10) to provide a species-wide distribution and abundance map. We then accessed a range of environmental and landscape data files which were uploaded onto ArcMap and converted to rasters to enable a correlation with the presence / absence data. The following environmental and landscape data files were used:

- climate (BOM 2016)
    - temperature
        - mean annual
        - maximum annual
        - minimum annual
    - rainfall
        - rainfall zone
        - mean annual
        - mean winter
        - mean spring
        - variability annual
        - variability winter
        - variability spring
- soil
    - classification (Northcote *et al.* 1968)

- clay content (Viscarra Rossel *et al.* 2014b)
- sand content (Viscarra Rossel *et al.* 2014c)
- silt content (Viscarra Rossel *et al.* 2014d)
- depth (Viscarra Rossel *et al.* 2014e)
- bulk density (Viscarra Rossel *et al.* 2014a)
- depth to regolith (Wilford *et al.* 2015)

- aridity index (Trabucco and Zomer 2009)
- major vegetation sub-groups (DoEE 2018)
- land-use (ACLUMP 2016)
- slope (Gallant and Austin 2012)

The environmental data associated with each of the presence / absence points were extracted from the data files using the ArcMap 'Extract Values to Points' tool. The ArcMap attribute table containing all the presence / absence points with their correlated environmental data was exported to an Excel spreadsheet, which was then converted into an IBM SPSS (version 25) dataset for statistical analysis.

All statistical tests were performed in SPSS, and all maps were constructed using ArcMap. Satellite imagery was obtained from either Google Earth Pro (version 7) or Bing Maps on-line. The statistical analyses were conducted by comparing the data-points to the environmental and landscape data both individually (single factor analysis) and in combination (multi-factor analysis).

*Single factor analysis*

Single factor analysis was undertaken to provide descriptive statistics (mean, standard deviation, range) for each variable, with the results presented in graphical and textual form. In order to examine the data for the appropriate tests to use, we visually checked histogram / box-plots and examined each scale variable using the 'Explore' function in SPSS (Lilliefors corrected K-S test), which provided information on normality (skewness, kurtosis, Q-Q plot (normal and de-trended), 5% trimmed mean). Related continuous variables (e.g. soil at different depths, min / mean / max temperature) were checked for correlation using either a Pearson (linear, homoscedastic, skewness of both variables $< .5$) or Spearman's rank-order test. Where a correlation existed, only one selected variable is presented. Chi-square or Fisher's exact tests were performed to determine the significance of any differences between expected and observed frequencies of categorical variables compared to the presence / absence data.

*Multi-factor analysis*

Multi-factor analysis was undertaken using the machine-learning / data-mining technique 'Association Rules Learning' (Agrawal *et al.* 1993; Koperski and Han 1995); a rules-based machine-learning method used for discovering relationships between variables in large databases (our database contains ~ 480,000 data points), including in the field of bioinformatics (Raza 2012), and available via the SPSS 'Spatial and Temporal Modelling' tool. The aim was to create a set of 'rules' which predict the likelihood that wombats might be absent or present across their distribution based on combinations of environmental and landscape variables (Kobler and Adamic 2000).

The variables used in the multi-factor analysis were based on the results from the single factor analysis. The results were used to reduce the number of variables used in the analysis by selecting only one variable from each group of correlated related variables based on the results of the Pearson or Spearman's rank-order test. The variables used for the analysis were:

- mean annual temperature
- mean annual rainfall
- index of winter rainfall variability
- aridity index
- soil clay content
- vegetation sub-groups
- land-use categories

As we did not have any land-use data for Western Australia, the analysis was conducted on two levels. Level one analysis included presence / absence data for all regions (including Western Australia), but excluded land-use categories. Level two analysis excluded Western Australia but added land-use data for all South Australian regions.

Rules were ranked by 'Lift', the ratio of rule confidence to the prior probability of the rule occurring (i.e. the ratio of how well the rule describes the increase in likelihood of presence /

absence occurring compared to chance). Rules were placed in rank order and presented in tables which also included:

- Condition support – the proportion of items in the database for which the condition is true.
- Confidence – the ratio of rule support to condition support. Of all the individual data points in the database, the percentage that has the predicted values.
- Rule support – the percentage of all items in the dataset which is correctly accounted for and predicted by the rule (i.e. the overall importance of the rule).
- Deployability – the percentage of the training data which satisfies the condition but not the prediction (i.e. how often the rule is not valid).

Each rule was analysed to determine how often each variable occurred in the rule set, and rules were compared to determine if a change in one variable resulted in a change in predicted outcome (i.e. the variable was a critical factor). The results from the level one analysis were compared to the results from the level two analysis to reveal any differences.

**Results**

From the field surveys and analysis of satellite imagery, we collected 8,130 data points comprising 5,349 presence points and 2,781 absence points (Figure 1– presence points shown).

*Climate - temperature*

While we analysed the wombat distribution against mean, maximum and minimum temperatures, there was a significant correlation between all three metrics (Pearson correlation: mean / maximum $r = 0.950$, $n = 5349$, $p < .001$; mean / minimum $r = 0.754$ $n = 5349$, $p < .001$; maximum / minimum = 0.512 $n = 5349$, $p < .001$). Consequently, the mean temperature results only are shown here.

Southern hairy-nosed wombats occur in regions with a mean annual temperature between 14.12 – 19.45$^{o}$C ($\bar{x} = 17.52^{o}$C; $\sigma = 0.82$), with 90% of the distribution occurring within the range of 16.15 – 19.04$^{o}$C (5% trimmed mean = 17.52, skewness = -.424, kurtosis = .165) (Figure 2). The mean annual temperature and range of mean temperatures varies from region to region, with those further to the north (Gawler Ranges / Lake Harris; Nullarbor Plain) having the highest mean temperatures (Gawler Ranges / Lake Harris = 18.18 $^{o}$C; Nullarbor Plains = 17.86

°C) and those with the greatest north-south extent having the greatest range (Gawler Ranges / Lake Harris = 16.37 – 19.45 °C) (Figure 3).

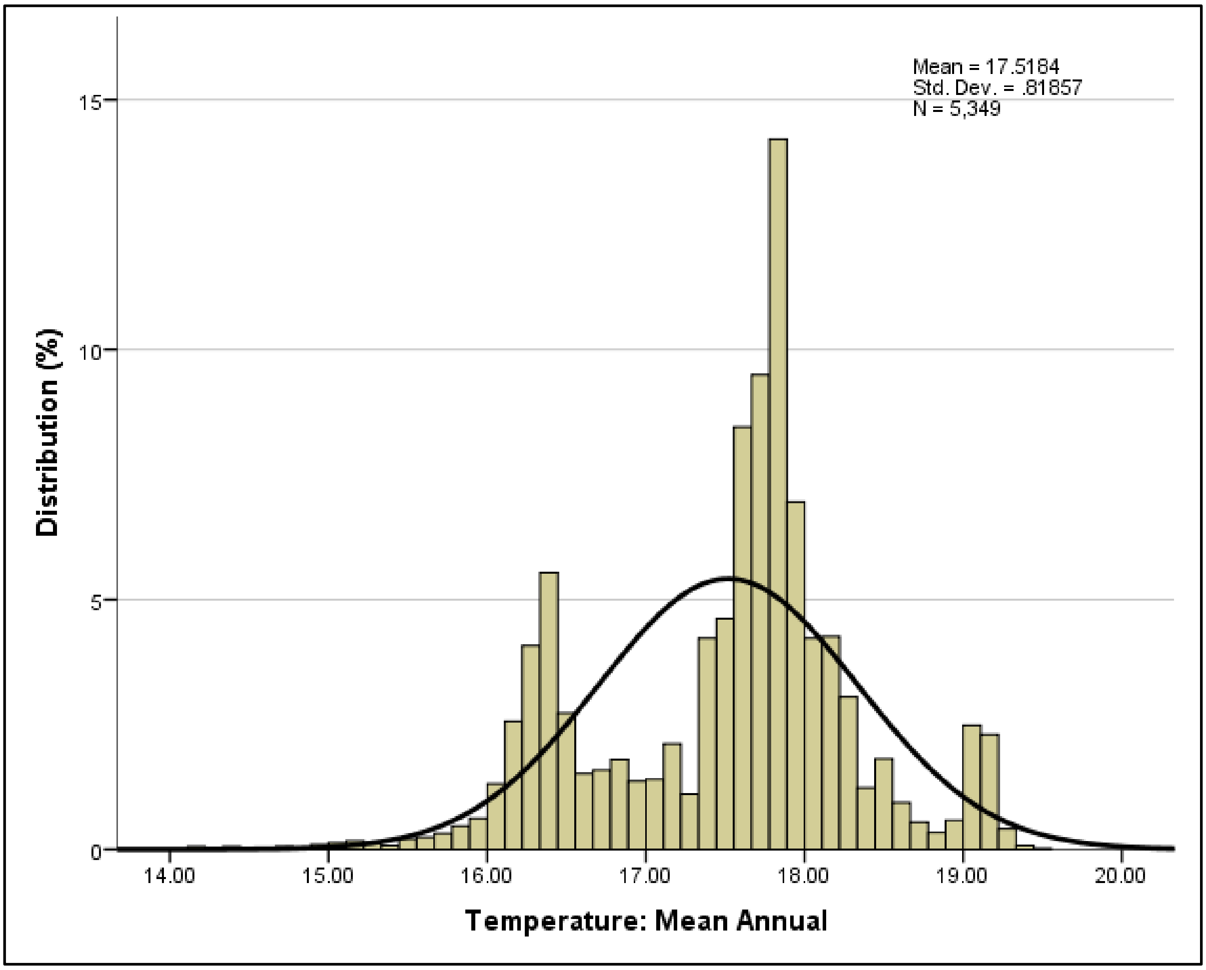


*Figure 2: Mean annual temperature across the southern hairy-nosed wombat distribution. The different 'peaks' in this graph represent the different regions where southern hairy-nosed wombats can be found (see Figure 3).*

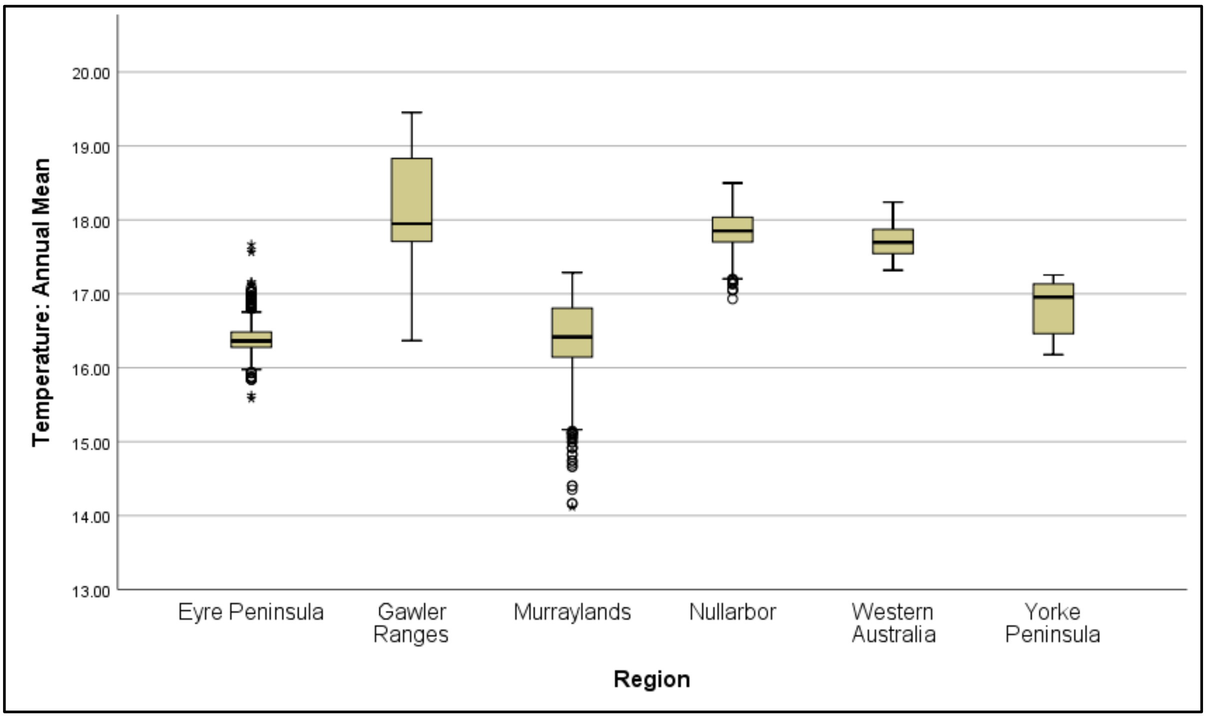


*Figure 3: Box and whisker plot of the mean annual temperature for each of the regions where southern hairy-nosed wombats can be found. The mean and range of mean temperatures for each region reflects their geographic distribution, with higher temperatures being found further to the north. The greater range of mean temperatures for the Gawler Ranges / Lake Harris and Murraylands reflects their more extensive north-south distribution.*

*Climate - rainfall*

Southern hairy-nosed wombats occur in regions where the majority of the rainfall occurs in winter (Figure 4). There is a significant correlation between the mean winter and the mean annual rainfall across the distribution (Spearman's rank-order correlation: $r = 0.992$, $n = 5349$, $p < .001$). Therefore, only the analysis of mean annual rainfall is shown.

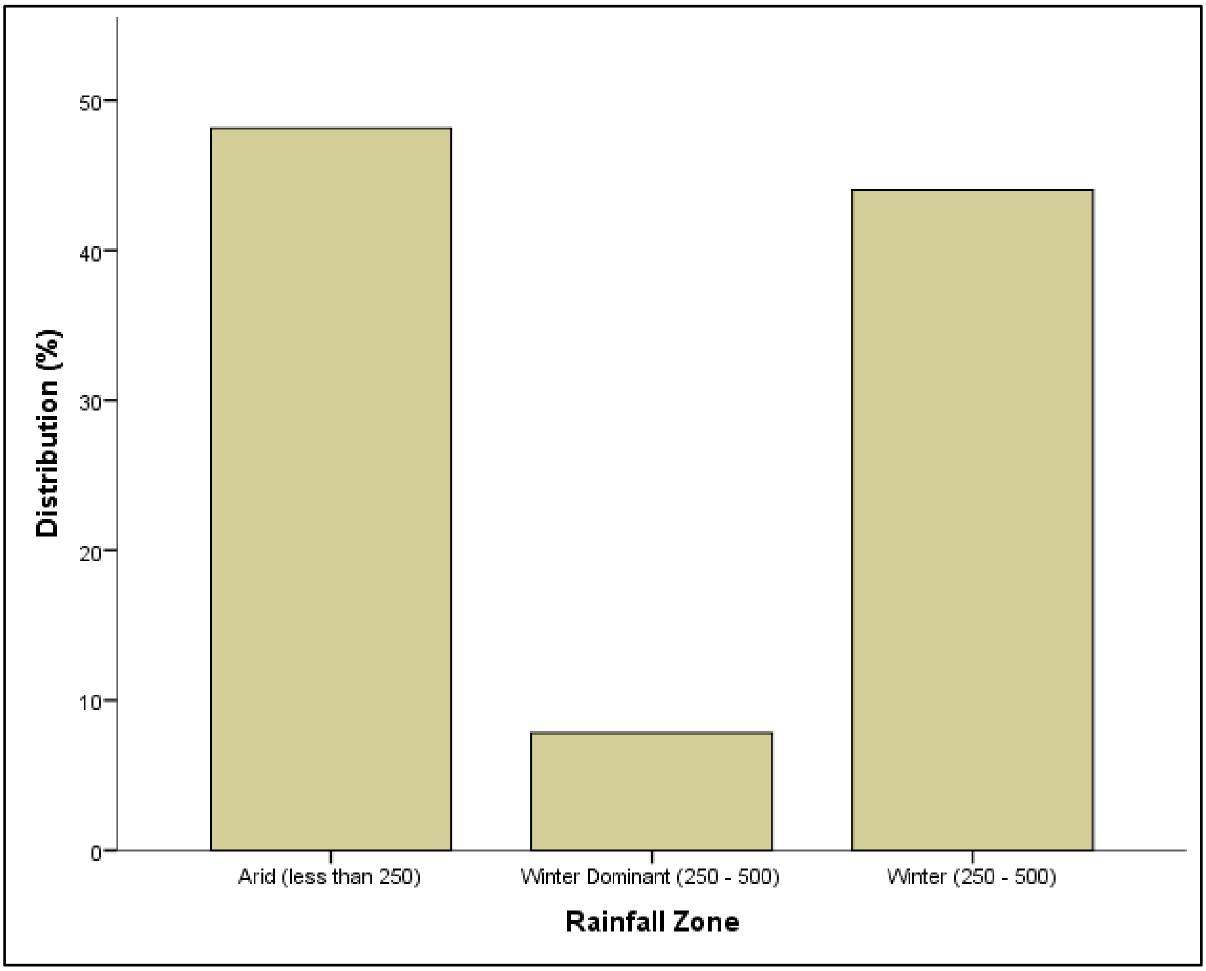


*Figure 4: Southern hairy-nosed wombat distribution, by rainfall zones. 'Winter Dominant' is defined as 'marked wet winter and dry summer', while 'Winter' is defined as 'wet winter and low summer rainfall' (BOM 2016).*

Approximately half ($\hat{p}$ = 0.48) of the southern hairy-nosed wombat distribution occurs in the arid zone where the mean annual rainfall is < 250 mm / annum ($\overline{x}$ = 255.57 mm / annum; $\sigma$ = 63.44; range = 154 – 507 mm). 90% of the distribution occurs in regions with a mean annual rainfall between 170 – 405 mm / annum (5% trimmed mean = 251.0, skewness = 1.284, kurtosis = 1.415) (Figure 5). The amount of annual rain varies between regions, with higher rainfall occurring in regions further to the south, and in the southern areas of regions with a large north-south extent (Figure 6). Mean annual rainfall is negatively correlated with mean annual temperature (Spearman's rank-order correlation: r = -0.771, n = 5349, p < .001) (Figure 7).

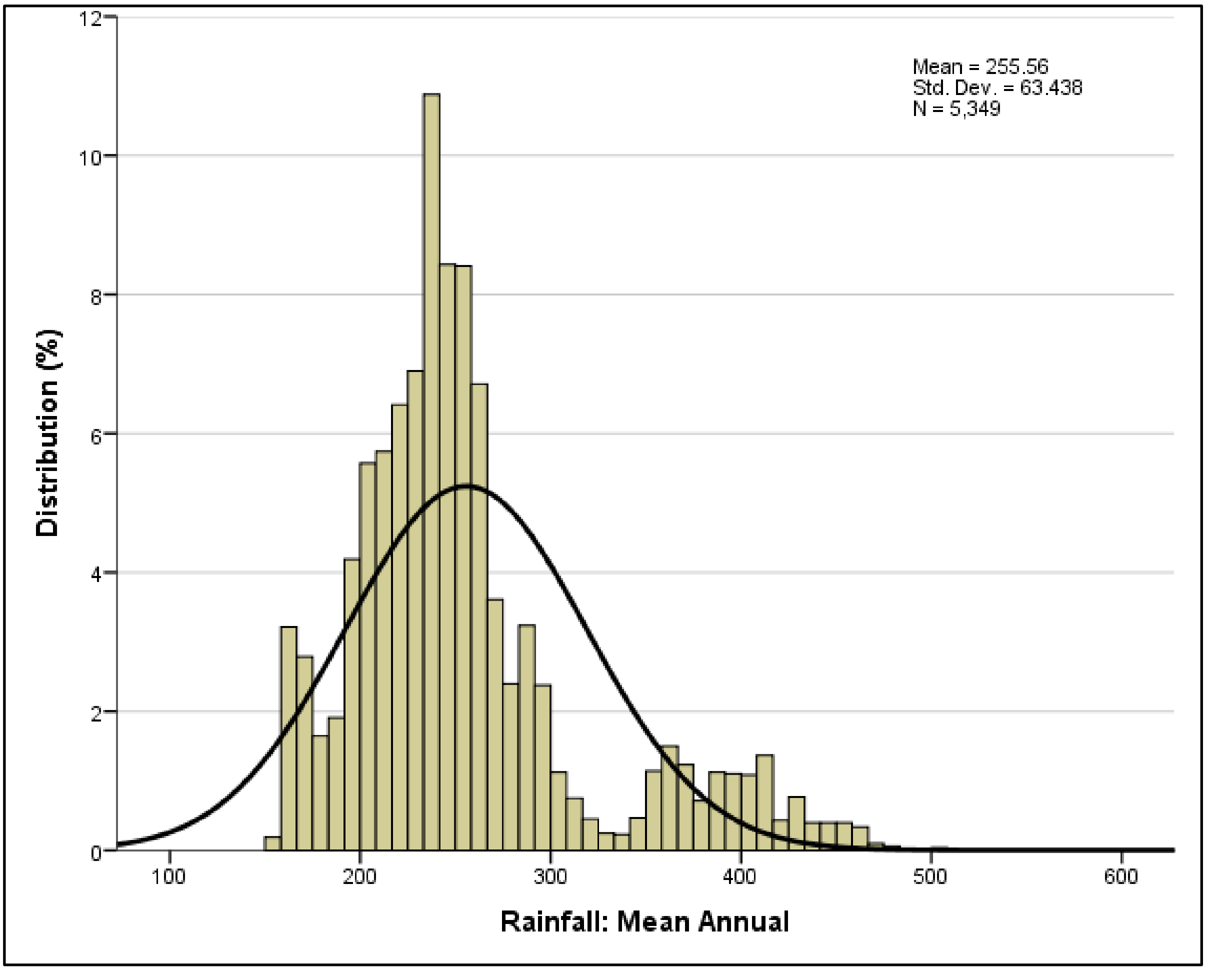


*Figure 5: Mean annual rainfall across the species-wide distribution of southern hairy-nosed wombats. The geographic shape of the species-wide distribution is not evenly distributed across rainfall zones, as there is a southerly 'tail' because of the Murraylands, and Eyre and Yorke Peninsulas. We would therefore expect the distribution to be skewed, with a longer tail towards higher rainfall.*

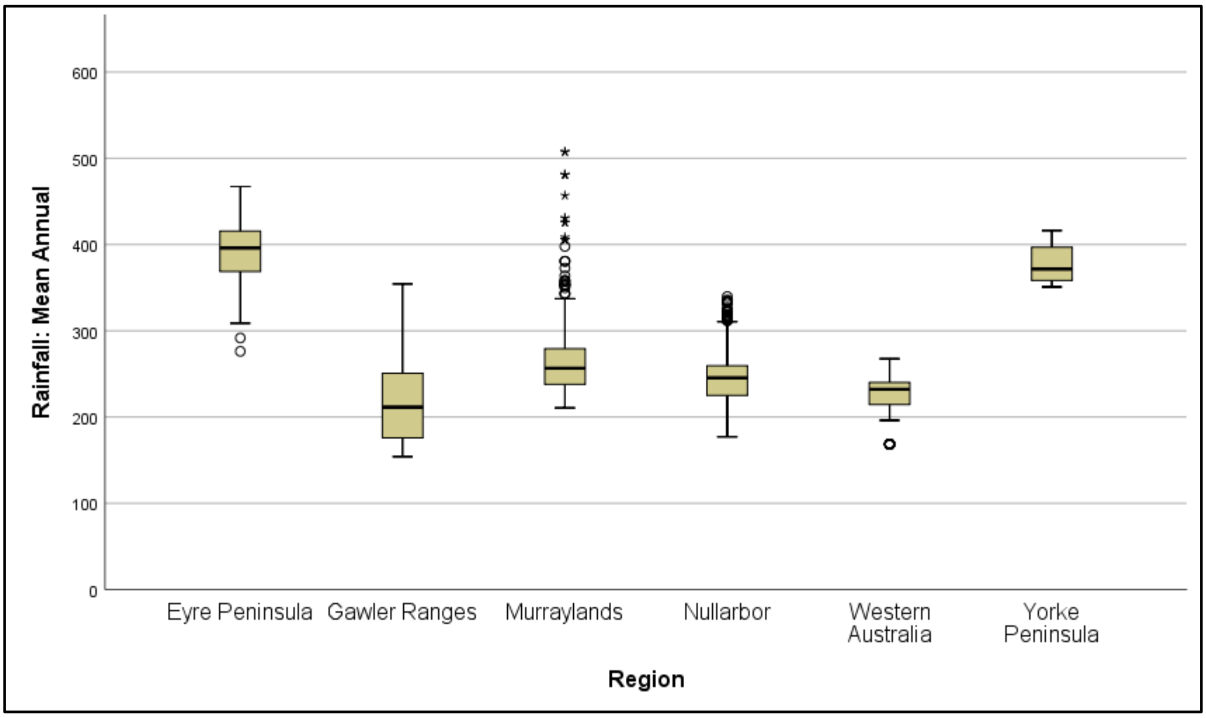


*Figure 6: Box and whisker plot of the mean annual rainfall for each of the regions where southern hairy-nosed wombats can be found. While temperatures increase further to the north, rainfall decreases.*

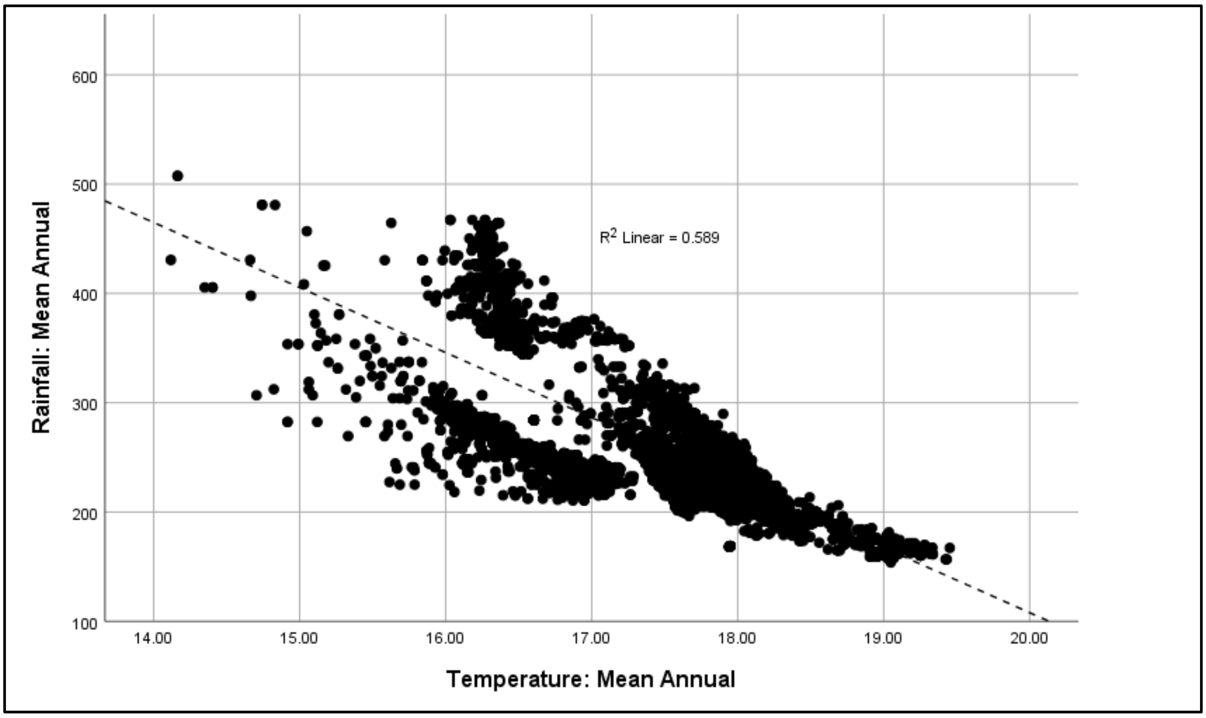


*Figure 7: Relationship between mean annual rainfall and mean annual temperature across the distribution of southern hairy-nosed wombats. There is a significant negative correlation between the two variables (Spearman's rank-order correlation: r = -0.771, n = 5349, p < .001)*

*Climate – rainfall variability*

Rainfall variability is a measure of the difference in the amount of rain which falls from year to year. The index of variability is calculated by subtracting the 10th rainfall percentile (the lowest 10% of records) from the 90th percentile (the highest 10% of records), divided by the 50th percentile (median). The higher the index, the higher the variability. Indices from 0 – 0.5 are considered to be low variability; 0.5 – 0.75 is low-moderate; 0.75 – 1.0 is moderate; 1.0 – 1.25 is moderate-high; 1.25 – 1.5 is high; 1.5 – 2.0 is considered very high; and > 2.0 is extreme.

As is the case for rainfall and temperature, while we analysed annual and seasonal rainfall variability, there was a significant correlation between each of the paired cases (annual with each season and between seasons: Spearman's rank-order correlation for all paired cases $r > .556$, $n = 5349$, $p < .001$), with the strongest correlation between the annual and winter rainfall variability (Spearman's rank-order correlation $r = 0.923$, $n = 5349$, $p < .001$). As the majority of the wombat distribution occurs in regions where winter rainfall is dominant, and winter rainfall is considered to be important for wombat reproduction and recruitment (Gaughwin *et al.* 1998), only winter rainfall variability is shown.

The mean index of winter rainfall variability across the distribution of southern hairy-nosed wombats is 1.15 (moderate – high) ($\sigma = 0.25$; range = 0.71 – 1.97). 90% of the distribution occurs within a winter rainfall variability index of 0.82 – 1.65 (5% trimmed mean = 1.14, skewness = -.542, kurtosis = .118). There was variation between the different regions, with greater rainfall variability occurring in the more northerly regions and in the northern areas of all regions (Figure 8).

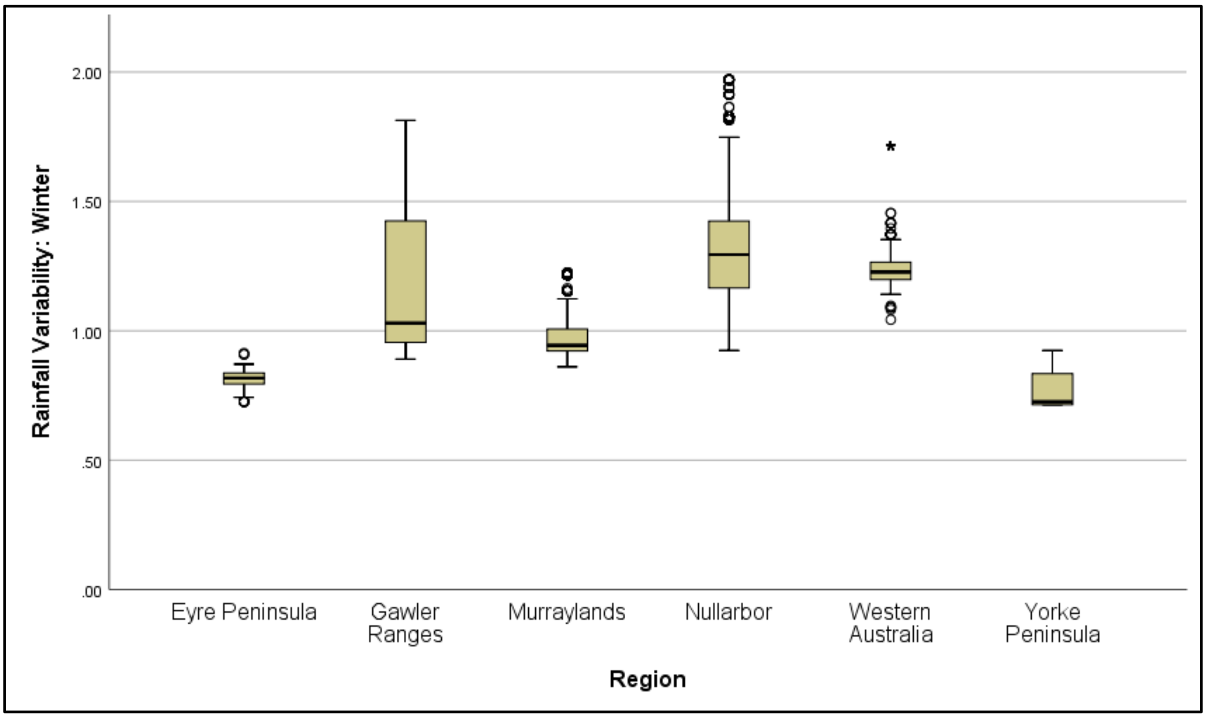


*Figure 8: Indices of rainfall variability during the important winter rainfall season for each region. Indices from 0 – 0.5 are considered to be low variability; 0.5 – 0.75 is low-moderate; 0.75 – 1.0 is moderate; 1.0 – 1.25 is moderate-high; 1.25 – 1.5 is high; 1.5 – 2.0 is considered very high; and >2.0 is extreme.*

*Soil - type*

Most of the southern hairy-nosed wombat distribution ($\hat{p}$ = 0.85) occurs in areas dominated by calcarosols (Figure 9). However, there are differences between the regions (Figure 10). While on both the Nullarbor Plain and Western Australia all of the wombat distribution occurs in calcarosols ($\hat{p}$ = 1.00), in the Gawler Ranges only half ($\hat{p}$ = 0.51) occurs in calcarosols, with $\hat{p}$ = 0.37 occurring in areas of tenosol soils, $\hat{p}$ = 0.07 in hydrosols and $\hat{p}$ = 0.05 in rudosols. On the Eyre Peninsula $\hat{p}$ = 0.84 occurs in calcarosols and $\hat{p}$ = 0.16 in kandosols, and in the Murraylands $\hat{p}$ = 0.94 occurs in calcarosols, with the remainder evenly divided between sodosols and tenosols ($\hat{p}$ = 0.03 each).

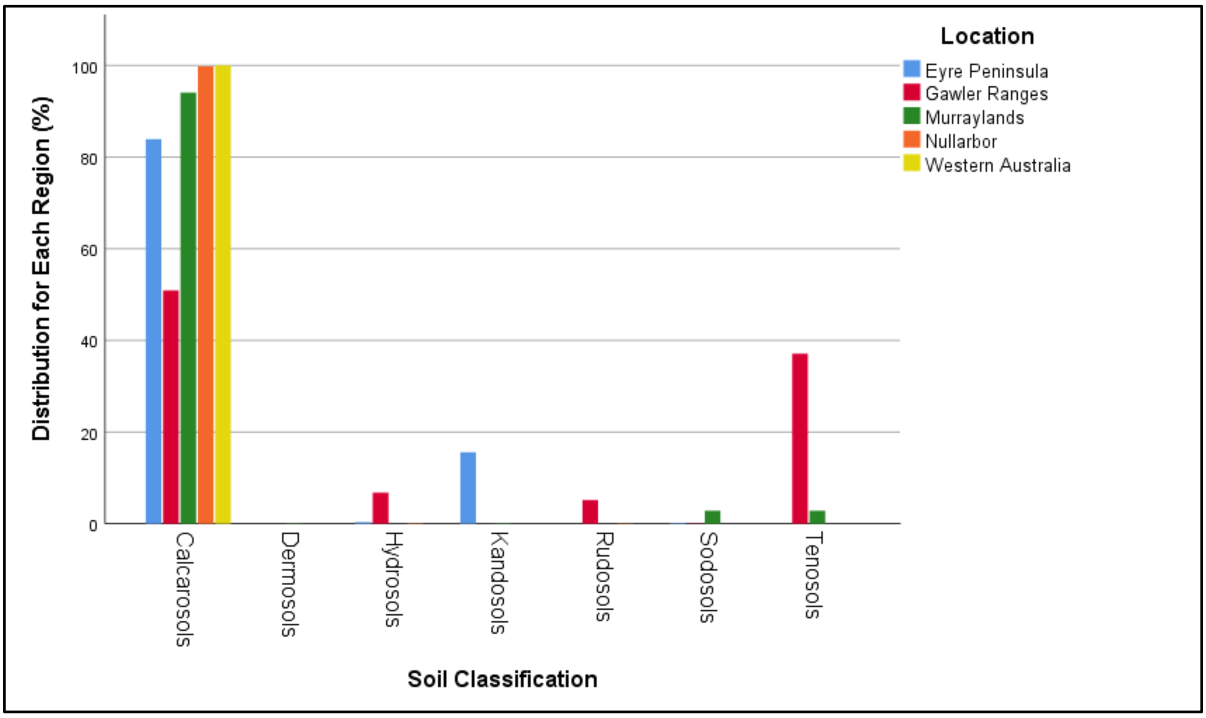


*Figure 9: Southern hairy-nosed wombat distribution for each region by soil classification. Although ~ 85 % of the entire distribution occurs in calcarosols, in some regions a high proportion occurs in other soil types. For example, in the Gawler Ranges region, only ~ 51 % of the distribution occurs in calcarosol soils, while ~ 37 % (the Lake Acraman population in the southern part of the region within the Gawler Ranges proper) occurs in tenosol soils.*

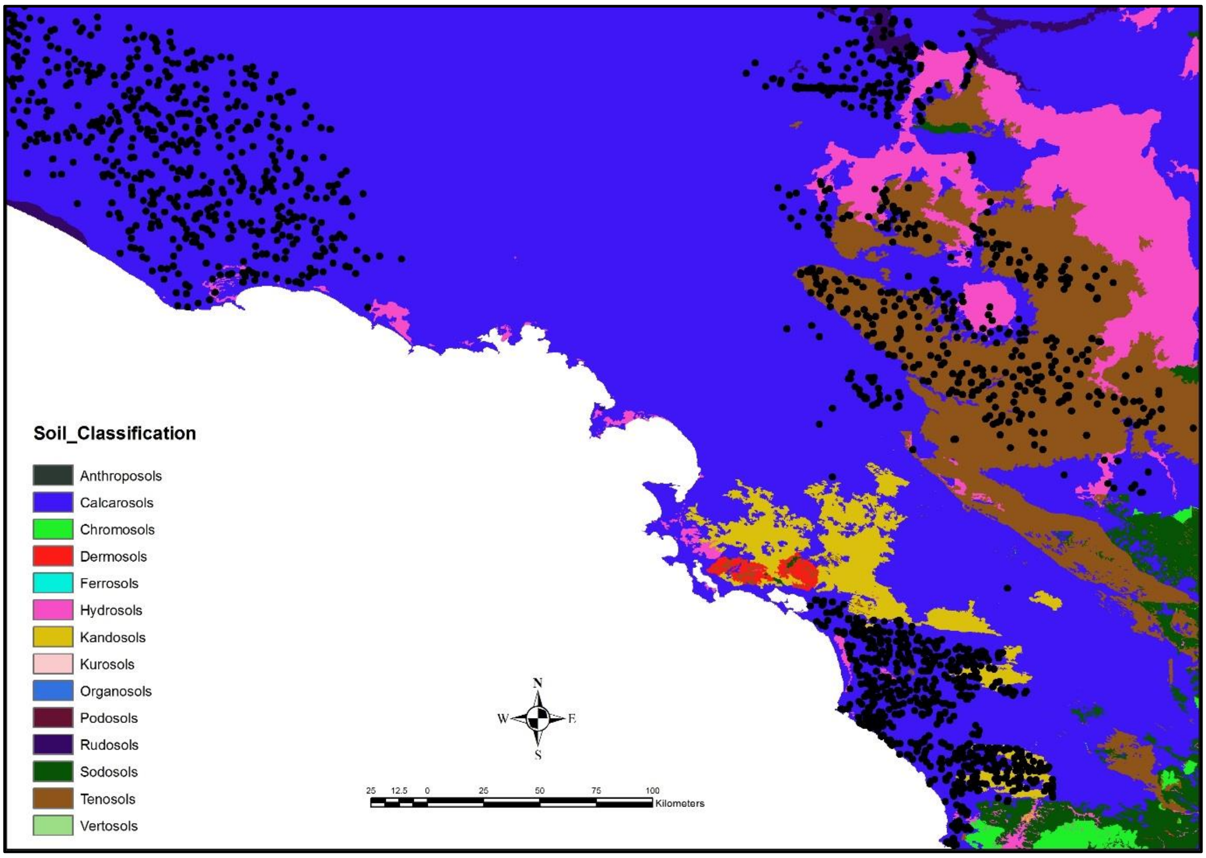


*Figure 10: Soil classification map of the area between the Nullarbor Plains wombat population (black dots in top left of image), Eyre Peninsula (bottom right) and Gawler Ranges (top right), showing the different soil types where wombats can be found. Although the wombat distribution occurs predominantly in calcarosols (blue), the southern half of the Gawler Ranges population around Lake Acraman occurs in tenosols (brown), and a significant proportion ($\hat{p}$ = 0.16) of the Eyre Peninsula population occurs in kandosols (yellow).*

*Soil – clay / sand / silt content*

There is a significant correlation between the sand, clay and silt content of soils at the different depths we analysed (0 – 5 cm; 5 – 15 cm; 15 – 30 cm; 30 – 60 cm; 60 – 100 cm; 100 – 200 cm) (pair-wise Pearson correlations between the different depths: clay - $r > .833$, $n = 5349$, $p < .001$; sand - $r > .891$, $n = 5349$, $p < .001$; silt - $r > .842$, $n = 5349$, $p < .001$). There is also a significant negative correlation between the proportion of sand and clay in the soils throughout the regions where southern hairy-nosed wombats construct their warrens (Pearson correlation: $r = -0.613$, $n = 5349$, $p < .001$) (Figure 11). Wombats only occur in areas where the soil clay content is between 8.9 – 39.9% ($\bar{x}$ = 22.8%; $\sigma$ = 4.1) and the sand content is between 41.0 – 87.9% ($\bar{x}$ = 63.3%; $\sigma$ = 8.1). 90% occur within the range of 16.4 – 28.2% clay (5% trimmed mean = 22.8, skewness = -.285, kurtosis = .374) (Figure 12) and 50.4 – 74.9% sand (5% trimmed mean = 63.4, skewness = -.143, kurtosis = .901) (Figure 13).

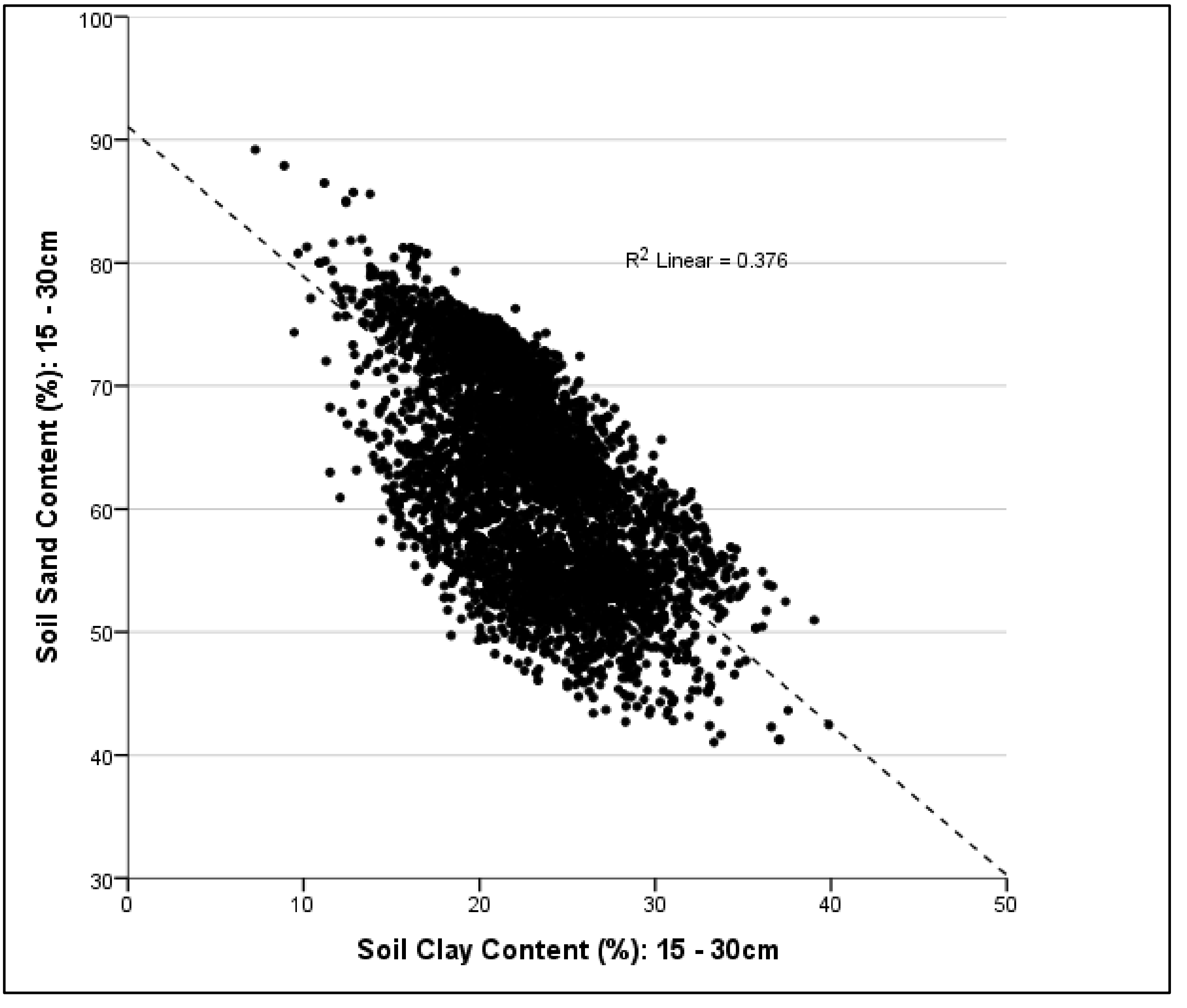


*Figure 11: The relationship between sand and clay content in the soil throughout the distribution of southern hairy-nosed wombats.*

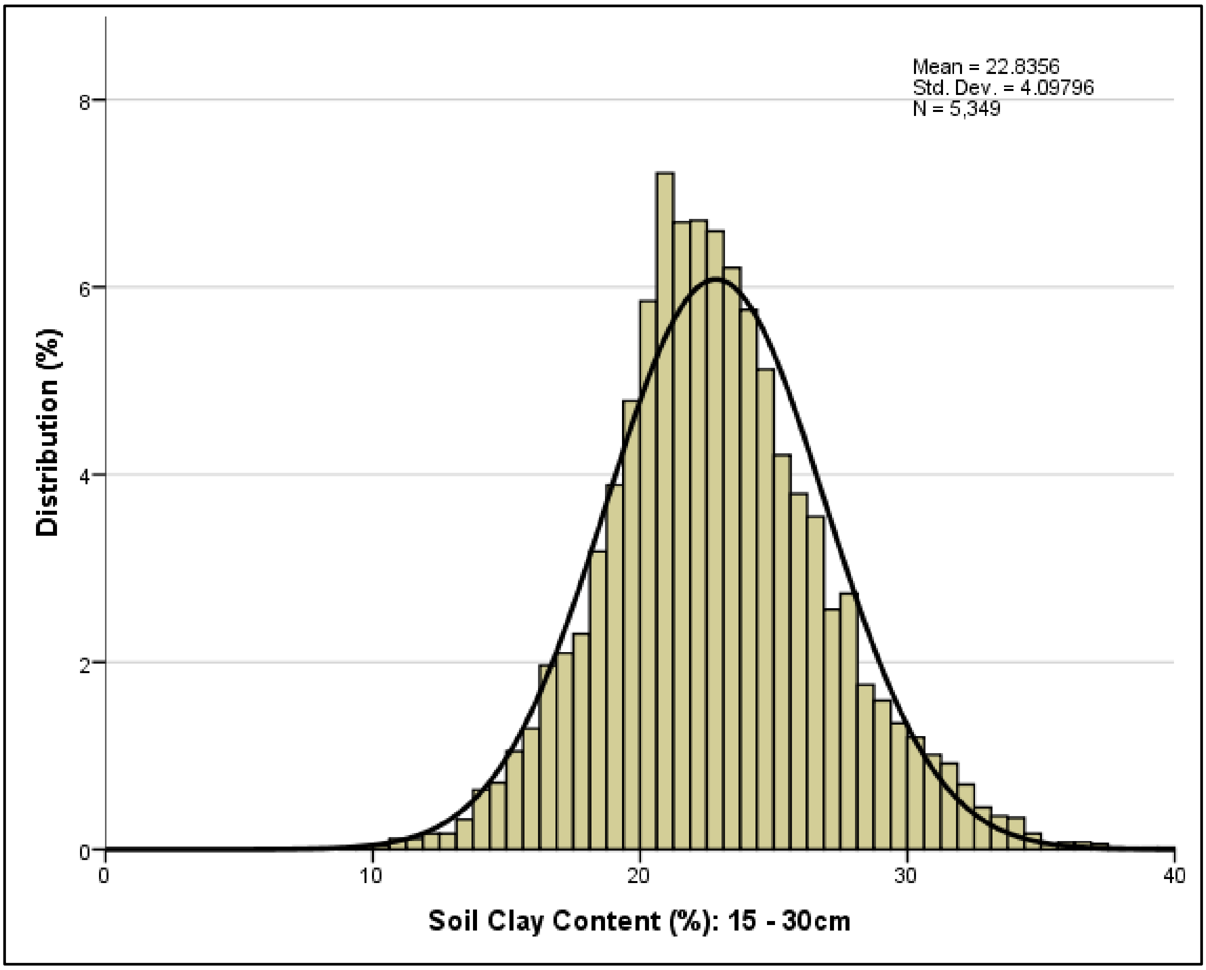


*Figure 12: Clay content (%) of the soil at a depth of 15 – 30 cm across the entire southern hairy-nosed wombat distribution (the clay content at other depths is similar). Soils with a clay content < 10 - 15% are likely to be too friable for warren stability, while soils with a high clay content retain water and can be more difficult to excavate when dry and hard.*

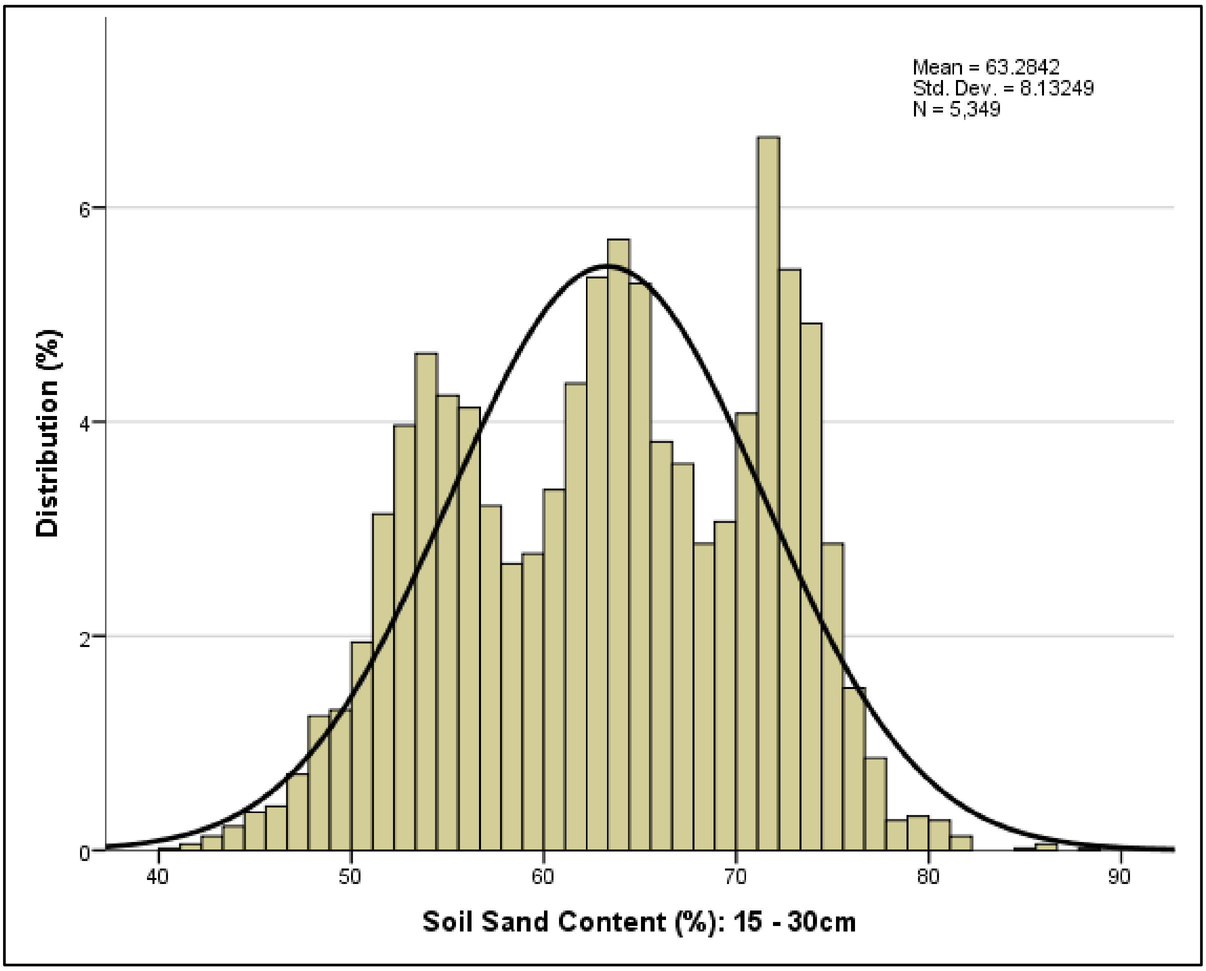


*Figure 13: Sand content (%) of the soil at a depth of 15 – 30 cm across the entire southern hairy-nosed wombat distribution. Soils with a high sand content are likely to be too friable for warren stability, while soils with a low sand content are likely to be difficult to excavate.*

The silt content of the soil across the distribution was between 1.0 – 11.5% ($\bar{x}$ = 5.9%; σ = 1.6), with 90% occurring within the range of 2.9 – 8.6% (5% trimmed mean = 5.9, skewness = -.361, kurtosis = -.262) (Figure 14).

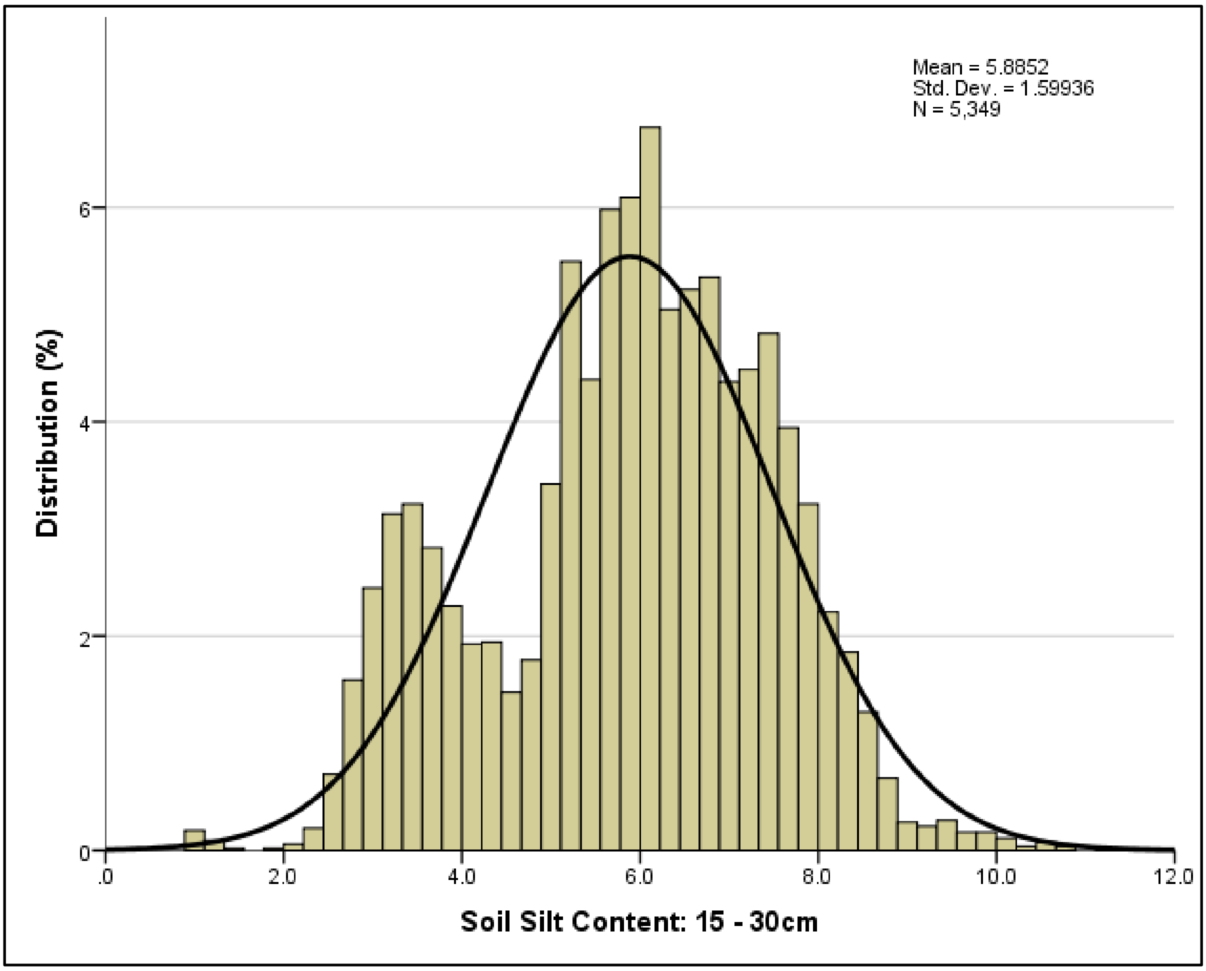


*Figure 14: Soil silt content across the southern hairy-nosed wombat distribution.*

*Soil – bulk density*

The bulk density of soil is the dry weight of the soil divided by its volume, expressed as $g/cm^3$. There is a significant correlation between the bulk density of the soil at the different depths we analysed (Pearson correlation: $r > .733$, $n = 5349$, $p < 0.001$). The bulk density of the soil across the southern hairy-nosed wombats' distribution is between 1.32 – 1.57 ($\bar{x}$ = 1.44%; $\sigma$ = 0.05). 90% of the distribution occurs within the range of 1.36 – 1.51 (5% trimmed mean = 1.44, skewness = -.118, kurtosis = -1.063) (Figure 15).

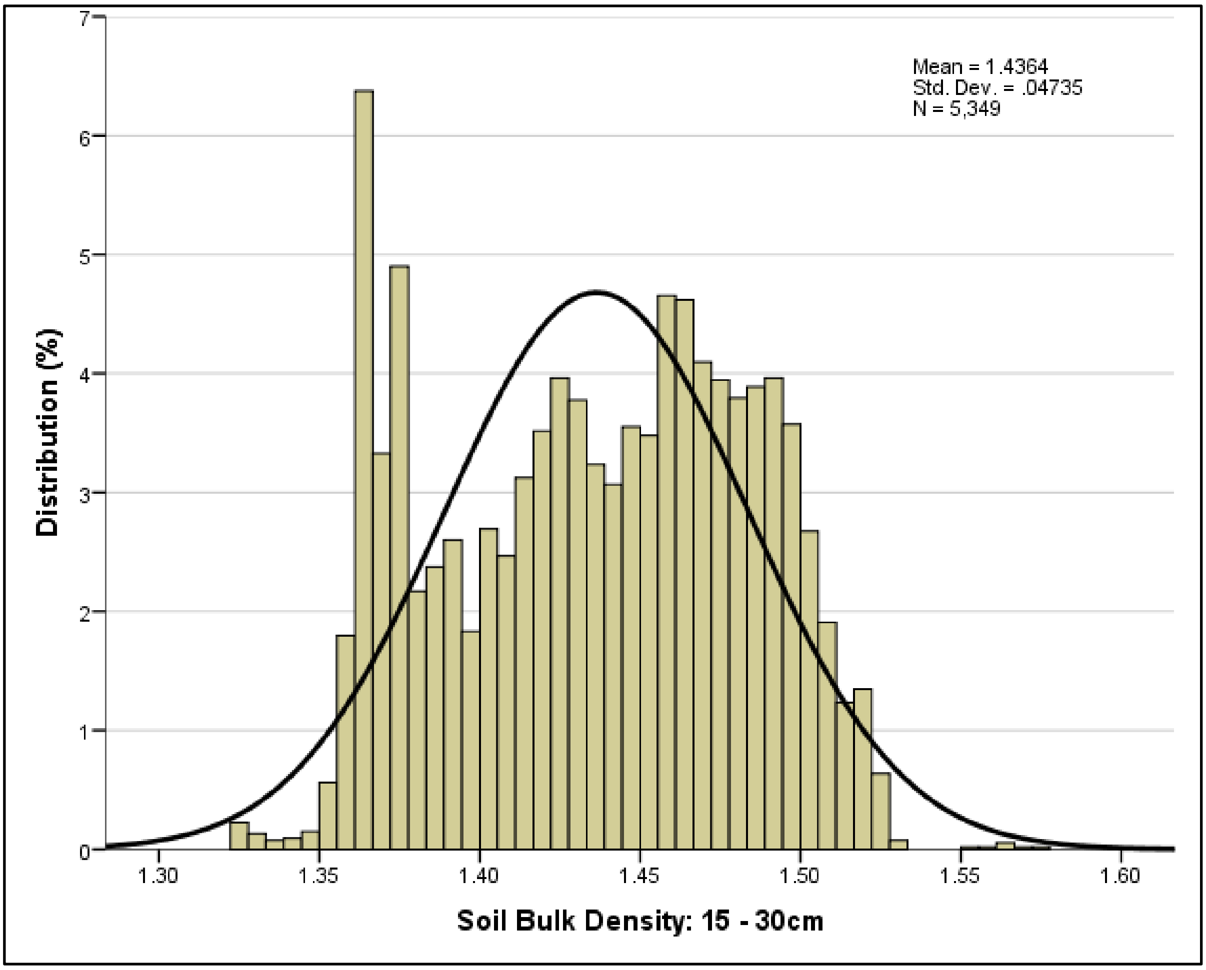


*Figure 15: Soil bulk density across the distribution of southern hairy-nosed wombats.*

*Soil – regolith terrain class / depth of regolith / soil depth*

Regolith is the layer of loose, heterogeneous deposits overlaying bedrock, and includes soil as the uppermost layer of biologically active material. Southern hairy-nosed wombats occur in 15 regolith terrain classes, with the four most common being ‘Nullarbor’ ($\hat{p}$ = 0.36), ‘Ceduna Dunefield’ ($\hat{p}$ = 0.23), ‘Gluepot’ ($\hat{p}$ = 0.13) and ‘Gawler Ranges’ ($\hat{p}$ = 0.10) (Figure 16). A description of the soil type in each of these regolith zones is contained in Table 1.

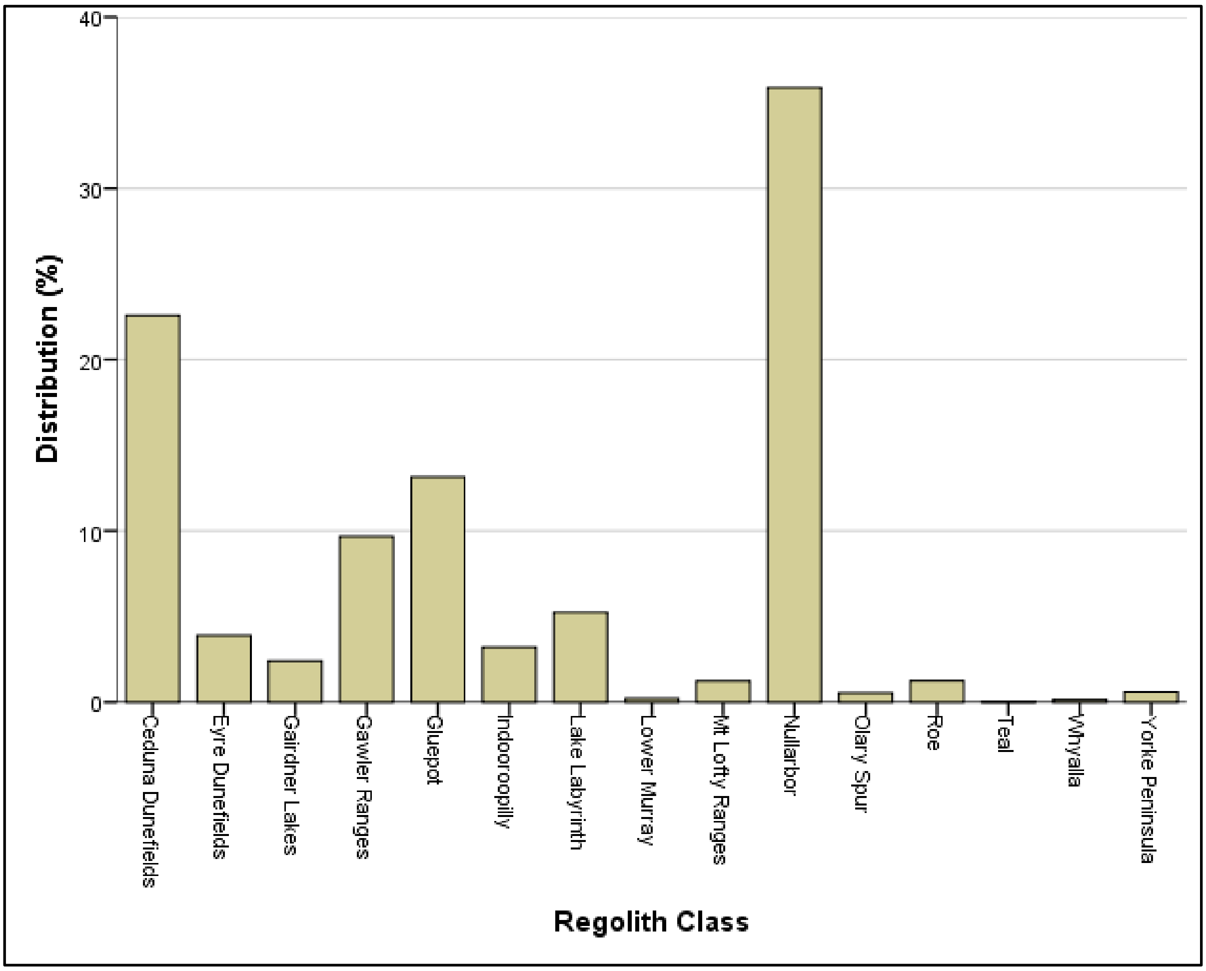


*Figure 16: Regolith terrain classes where southern hairy-nosed wombats can be found.:*

Regolith depth across the distribution of southern hairy-nosed wombats ranges from 0 – 115 m ($\bar{x}$ = 24.2 m; σ = 17.9), with 90% occurring in the range of 4.0 – 54.6 m (5% trimmed mean = 23.5, skewness = .556, kurtosis = -1.073) (Figure 17). Soil depth varies from 0.49 – 1.11 m ($\bar{x}$ = 0.75 m; σ = 0.14). However, the reliability of this soil depth is questionable, as the metadata for the soil maps acknowledges that in some locations there may be little or no soil, and the data is based on the best estimates at a spatial scale of 90 m and may not accurately reflect local conditions (Viscarra Rossel *et al.* 2014e).

*Table 1: Soil descriptions for each regolith class where hairy-nosed wombats can be found. For a full description of the codes used in this table, refer to The Digital Atlas of Australian Soils (CSIRO 2013)*

| **Regolith Class** | **Soil Description** |
|---|---|
| Belyando | Red earths (Gn 2.12), yellow earths (Gn 2.22,2.21), self-mulching clays (Ug 5) |
| Ceduna Dunefield | Sandy soils of minimal pedologic development (Uc 1.11); Brown calcareous earths (Gc 1.12); Brown sand soils (Uc 5.11,5.12); Shallow red brown sandy soils (Uc 6.13); Sandy soils with yellow clayey mottled subsoil (Dy 5.43, Dy 3.42) |
| Eyre Dunefield | Sandy soils with weak pedologic development (Uc 5.21). Red calcareous earths (Uc 5.11,12,13). Red siliceous sands (Uc 1.2) |
| Gairdner Lake | Amorphous loamy soils (Um 5.41); Brown calcareous earths (Gc 1.1); Soils with weak horizon development (Uc 5.11,5.12); Crusty loamy soils with red clayey subsoils (Dr 1.33); Siliceous sands (Uc 1.2) |
| Gawler Ranges | Crusty loamy soils with red clayey subsoils (Dr 1.13,1.33); Brown calcareous earths (Gc 1.12,1.22); Amorphous loamy soils (Um 5.11) |
| Gluepot | Brown calcareous earths (Gc 1.12). Highly calcareous loamy earths Gc 1.12. Cracking clays, yellow grey (Ug 5.2). Hard setting loamy soils with red clayey subsoils (Dr 2.23) |
| Indooroopilly | Brown calcareous earths (Gc 1.22); Siliceous sand; loamy soils with weak pedologic development (Um 5.11). |
| Lake Labyrinth | Brown calcareous earths (Gc 1.12,1.22) |
| Lower Murray | Cracking clays (Ug5.2), brown sands (Uc 5.13, Uc 5) |
| Mt Lofty Ranges | Hard setting loams with red clayey subsoils (Dr 2.23,2.22); Highly calcareous loamy earths (Gc 1.12); Hard setting loams with mottled yellow clayey subsoil (Dy 3.42,3.22, Dy 3.61); Coherent sandy soils (Uc 6.11); Cracking clays (Ug 5.2). |
| Murray | Deep grey, self-mulching cracking clays (Ug 5.24 & .25) |
| Nullarbor | Shallow loamy calcareous soils (Um 5.11) |
| Olary Spur | Amorphous loamy soils (Um 5.11,5.41); Highly calcareous loamy earths (Gc 1.12); Crusty loamy soils with red clayey subsoils (Dr 1.13); Hard setting loamy soils with red clayey subsoil (Dr 2.23) |
| Roe | Brown calcareous earths (Gc 1.12,1.22). Loamy soils with weak pedologic development (Um 5.11). Calcareous sand (Uc 1.1) |
| Teal | Brown calcareous earths (Gc 1.13,33). Red earths (Gn 2.11). Loamy soils with weak pedologic development (Um 5.11) |
| Whyalla | Red calcareous earths (Gc 1.12), Sandy soils with mottled yellow clayey subsoils (Dy 5.43) |
| Yorke Peninsula | Brown calcareous earths (Gc 1.12, 1.22). Calcareous sands (Uc 1.11). Friable loamy soils (Um 6.24). Sandy soils with mottled yellow clayey subsoils (Dy 5.43). Highly calcareous loamy earths (Gc 1.12). Amorphous loams (Um 5.41). Red duplex (Dr 2.23) |

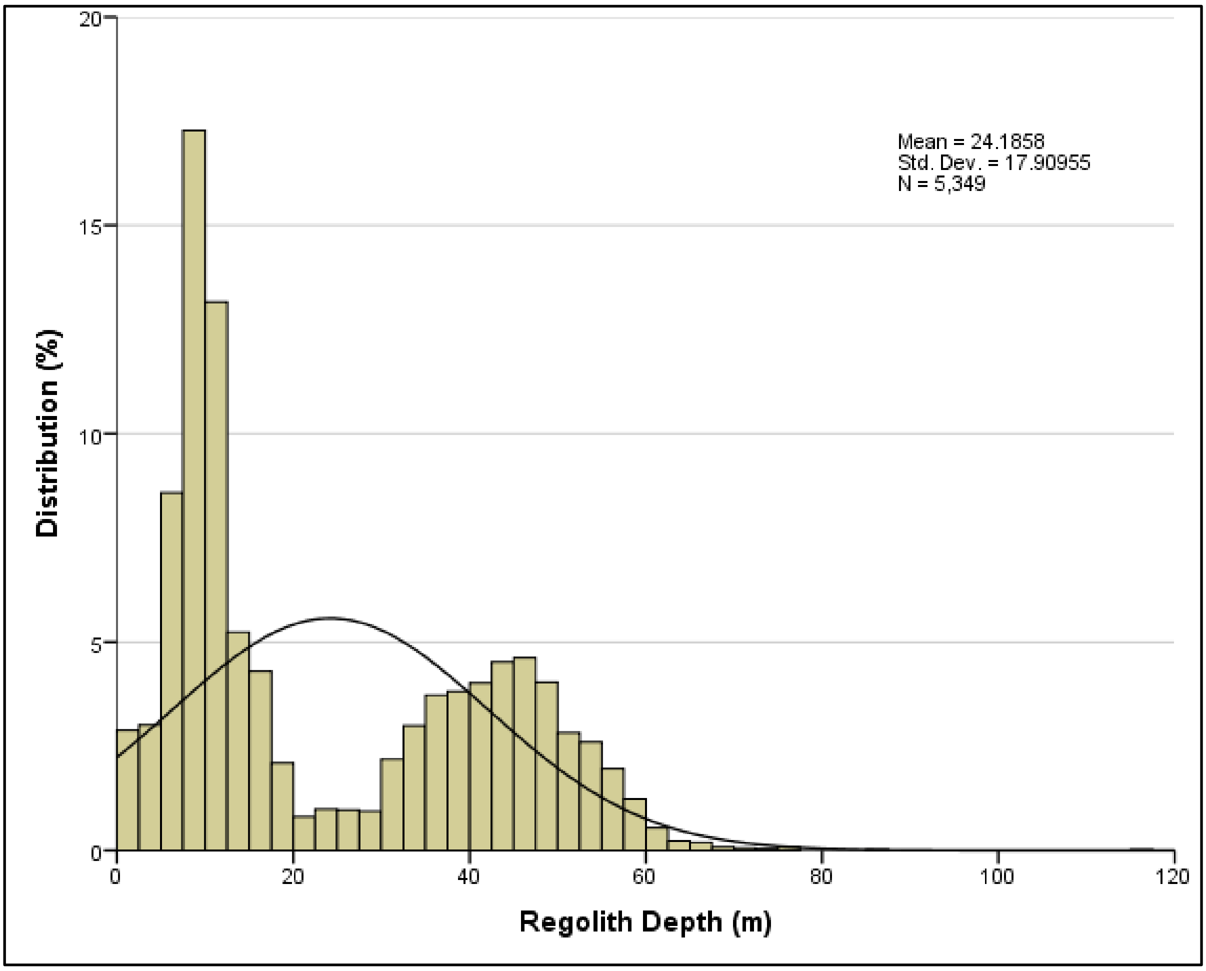


*Figure 17: Regolith depth across the southern hairy-nosed wombat distribution.*

*Aridity Index*

Aridity is a function of precipitation, temperature and potential evapotranspiration (PET). The Aridity Index (AI) can be used to quantify the availability of precipitation for soil and plant use, and is calculated by the formula:

(AI) = mean annual precipitation (MAP) / mean annual potential evapo-transpiration (MAE) (Trabucco and Zomer 2009)

MAE is based on the Hargreaves equation (Hargreaves and Allen 2003), which uses mean temperature (T*mean*), mean temperature range (TD) and mean extra-terrestrial radiation (RA: radiation at the top of the atmosphere) to calculate mean PET, as follows:

$$PET = 0.0023 \cdot RA \cdot (Tmean + 17.8) \cdot TD0.5 \text{ (mm / day)}$$

The aridity index across the distribution of southern hairy-nosed wombats is negatively correlated with temperature (Spearman's rank-order correlation: $r = -.786$, $n = 5349$, $p < .001$)

and positively correlated with rainfall (Spearman's rank-order correlation: r = .771, n = 5349, p < .001). Aridity indices < 0.03 are defined as 'hyper-arid'; 0.03 – 0.2 is 'arid'; and 0.2 – 0.5 is 'semi-arid'. Wombats occur in areas with aridity indices from 0.09 – 0.43 ($\overline{x}$ = 0.19; σ = 0.06), with 90% of the distribution occurring in the range of 0.11 - 0.33 (5% trimmed mean = 0.18, skewness = 1.524, kurtosis = 2.168) (Figure 18).

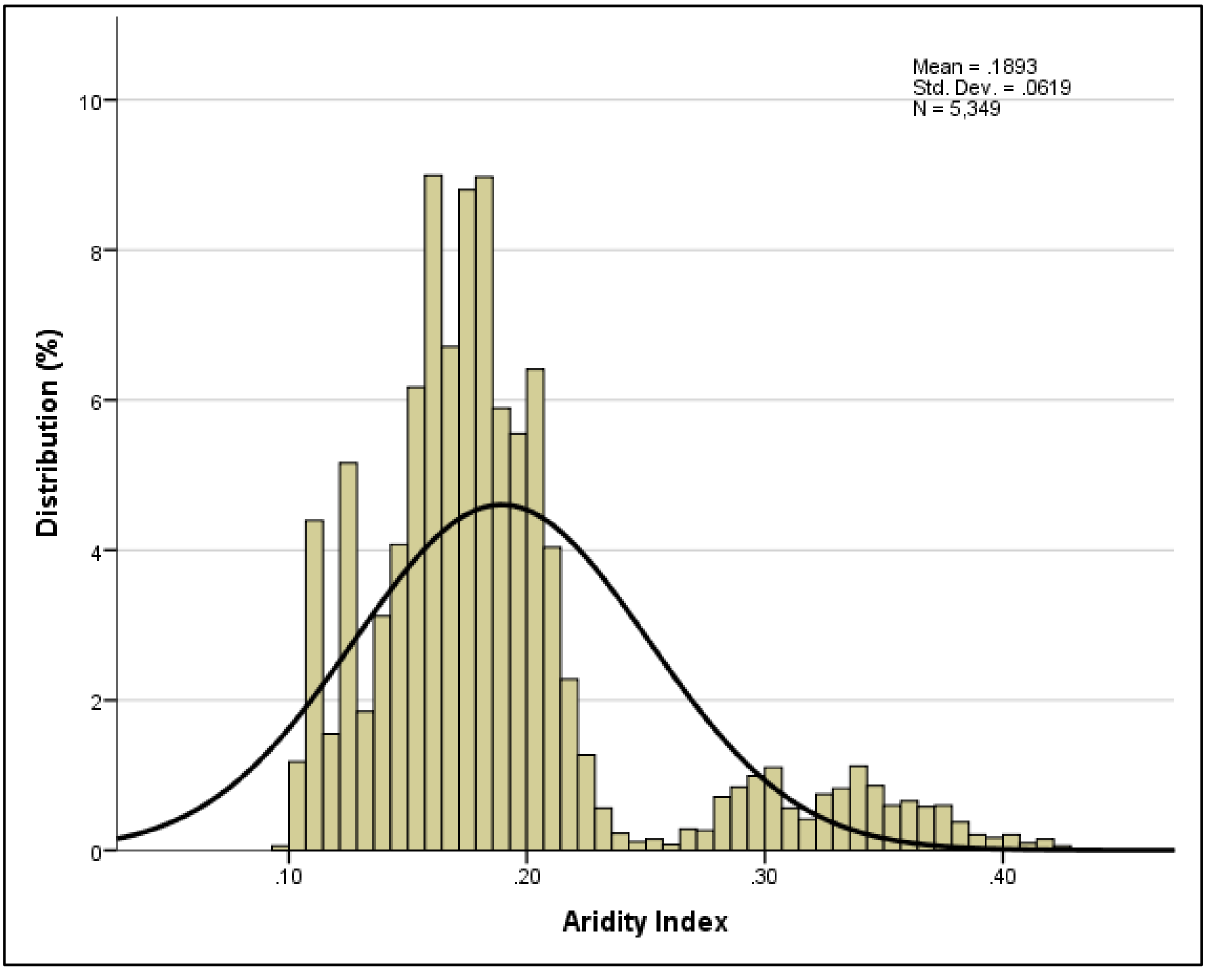


*Figure 18: Aridity index of the southern hairy-nosed wombat distribution. There are no wombats in areas which have an aridity index < 0.10.*

*Vegetation*

Southern hairy-nosed wombats can be found in twenty different vegetation types, with the most common being saltbush and bluebush scrublands ($\hat{p}$ = 0.50), followed by cleared areas with non-native vegetation ($\hat{p}$ = 0.13) (Figure 19).

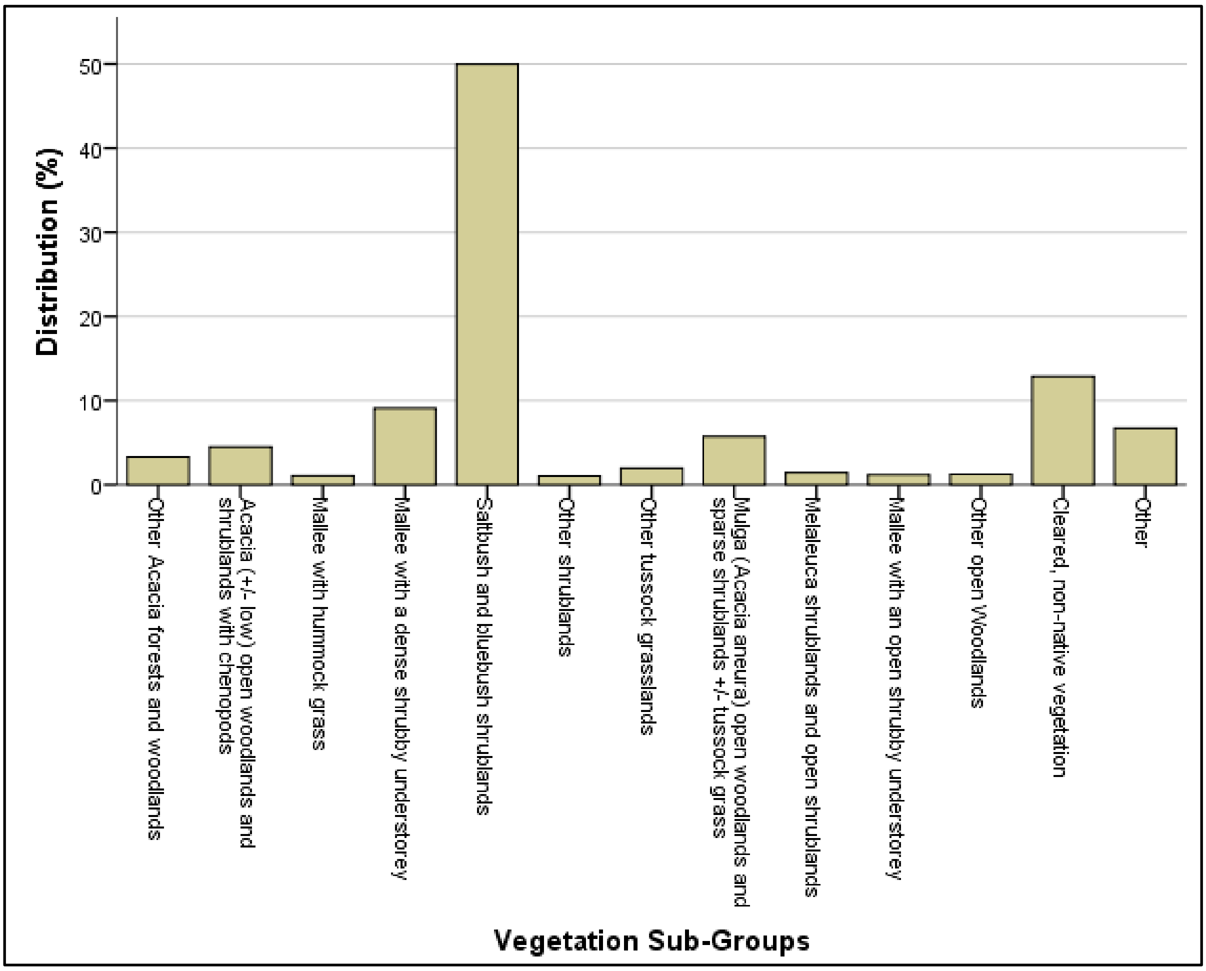


*Figure 19: Vegetation sub-groups where southern hairy-nosed wombats can be found. 'Other' consists of a collation of vegetation sub-groups which individually comprise* $< \hat{p} = 0.01$ *of the distribution.*

Due to a low number of data-points in some categories, a Fisher's exact test was performed to examine the relationship between presence / absence and vegetation sub-groups. The relationship between these variables was found to be significant (N = 8130, likelihood ratio = 425.036, df = 36, $p < .001$), with presence being affected by vegetation type. For example, the Murraylands region is comprised of 38.5% saltbush / bluebush shrublands (mainly in the northern half of the region), 37.3% cleared non-native vegetation (farmlands – mainly in the southern half of the region), 14.4% open woodlands, and 8.6% mallee with shrubby understory. But while wombats occupy 63.5% of the saltbush / bluebush shrublands, 65.9% of the farmlands, and 78.2% of the open woodlands, they only occupy 37.6% of the mallee shrublands. The density of the understory in the mallee also has an effect, with wombats being found in 44.6% of the mallee areas with open understory, versus 24.9% of the areas with dense understory (Figure 20).

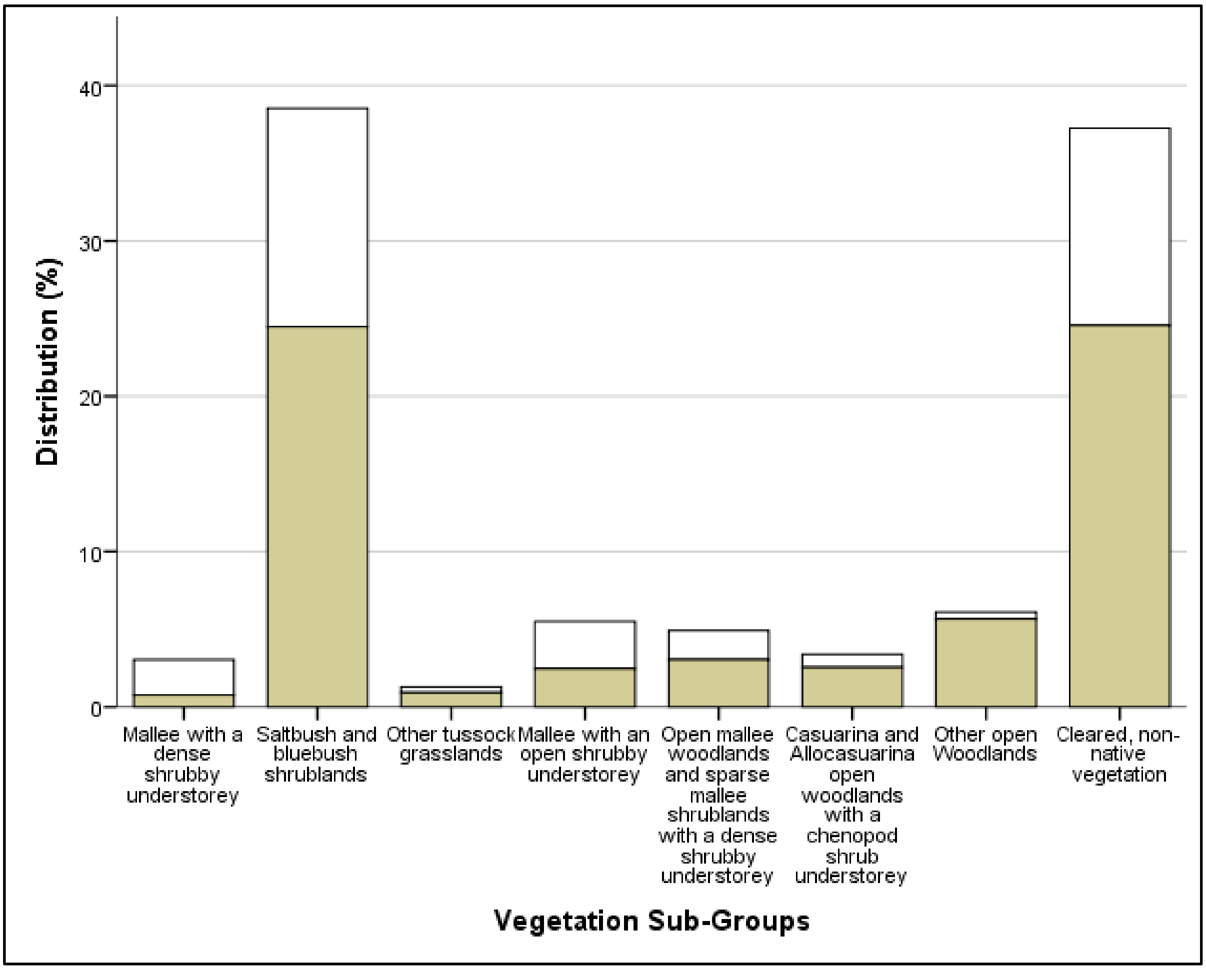


*Figure 20: Murraylands region showing the overall percentage of each vegetation class in the region, and the proportion of each class where wombats are present (brown). Note how wombats occupy the majority of each vegetation class, except for areas of mallee with both dense and open shrubby understory.*

Similar occupation rates are apparent in other regions. On the Eyre Peninsula, although there are no saltbush / bluebush shrublands, 49.8% of the region is comprised of cleared, non-native vegetation (grazing lands), 34.9% mallee with shrubby understory, 11% tussock grasslands and 2.9% open woodlands. While wombats occupy 70.5% of the grazing lands, 89.9% of the tussock grasslands and 82.1% of the open woodlands, they occupy only 35.0% of the mallee shrublands. On the Nullarbor, which is mostly saltbush / bluebush shrublands (76.9% of the region), 12.5% acacia and melaleuca open woodlands, and 4.0% mallee with dense shrubby understory, wombats occupy 72.2% of the saltbush / bluebush shrublands, 82.4% of the woodlands, but only 34.0% of the mallee areas.

*Land-use*

Southern hairy-nosed wombats occur across a variety of land-use types in South Australia, including protected areas ($\hat{p}$ = 0.38 (national parks = 0.09; other conserved areas = 0. 24; indigenous protected areas = 0.04)), crownlands (residual native cover; $\hat{p}$ = 0.07): grazing areas ($\hat{p}$ = 0.51 (native vegetation = 0.35, modified pastures = 0.15, native/exotic mosaic = 0.01); and cereal croplands ($\hat{p}$ = 0.02) (Figure 21). While a lack of available data prevented an analysis of the distribution in Western Australiar, the area where wombats occur is almost exclusively grazing on native vegetation, with some populations occurring on crown lands

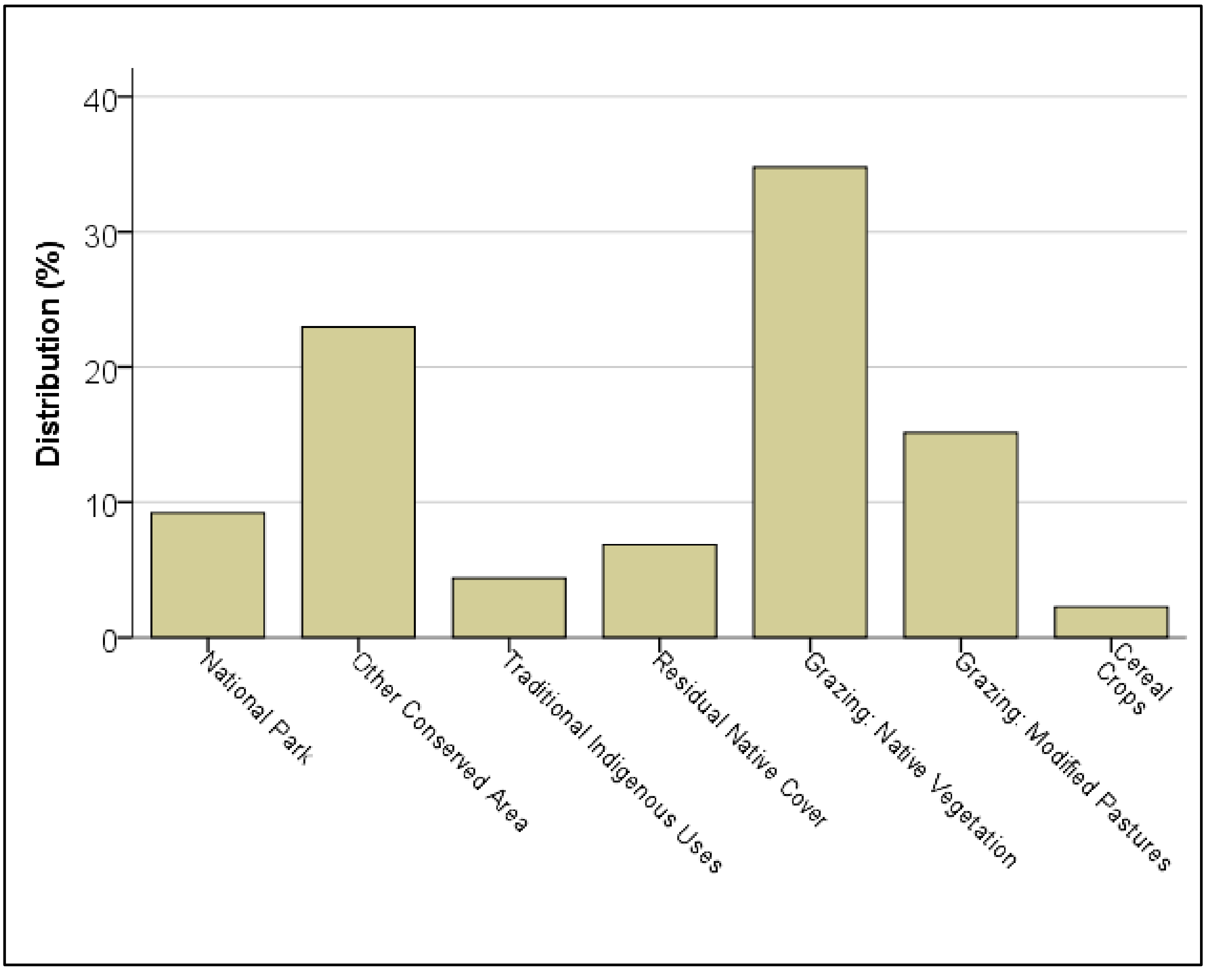


*Figure 21: Main land-use categories of the distribution of southern hairy-nosed wombats in South Australia (Western Australian population excluded from the analysis due to lack of available data). Note how only 2.3% of the population can be found in cropping areas, whereas 37.7% is located in protected/indigenous areas, and 49.9% is located on grazing land.*

*Terrain*

The majority of wombat warrens can be found on flat or near flat terrain ($\bar{x}$ = 0.8% slope; σ = 1.0) (Figure 22). Although some warrens can be found along steeper slopes, especially in creek banks (Figure 23), 90% of all warrens can be found on slopes of < 2.5º (5% trimmed mean = 0.7, skewness = 6.258, kurtosis = 88.439).

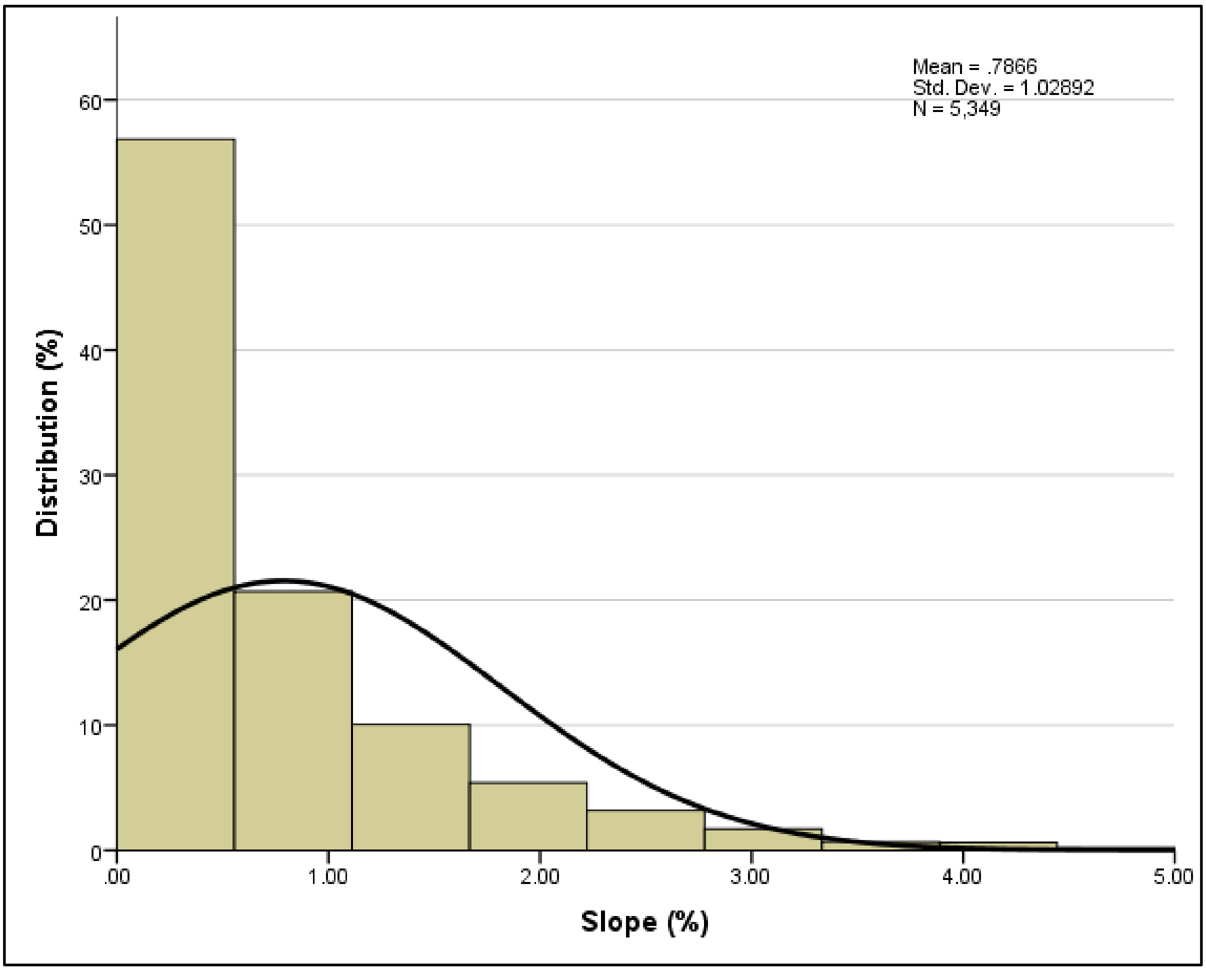


*Figure 22: Slope of the terrain where southern hairy-nosed wombats build their warrens. Virtually the entire distribution is found on flat or near flat terrain.*

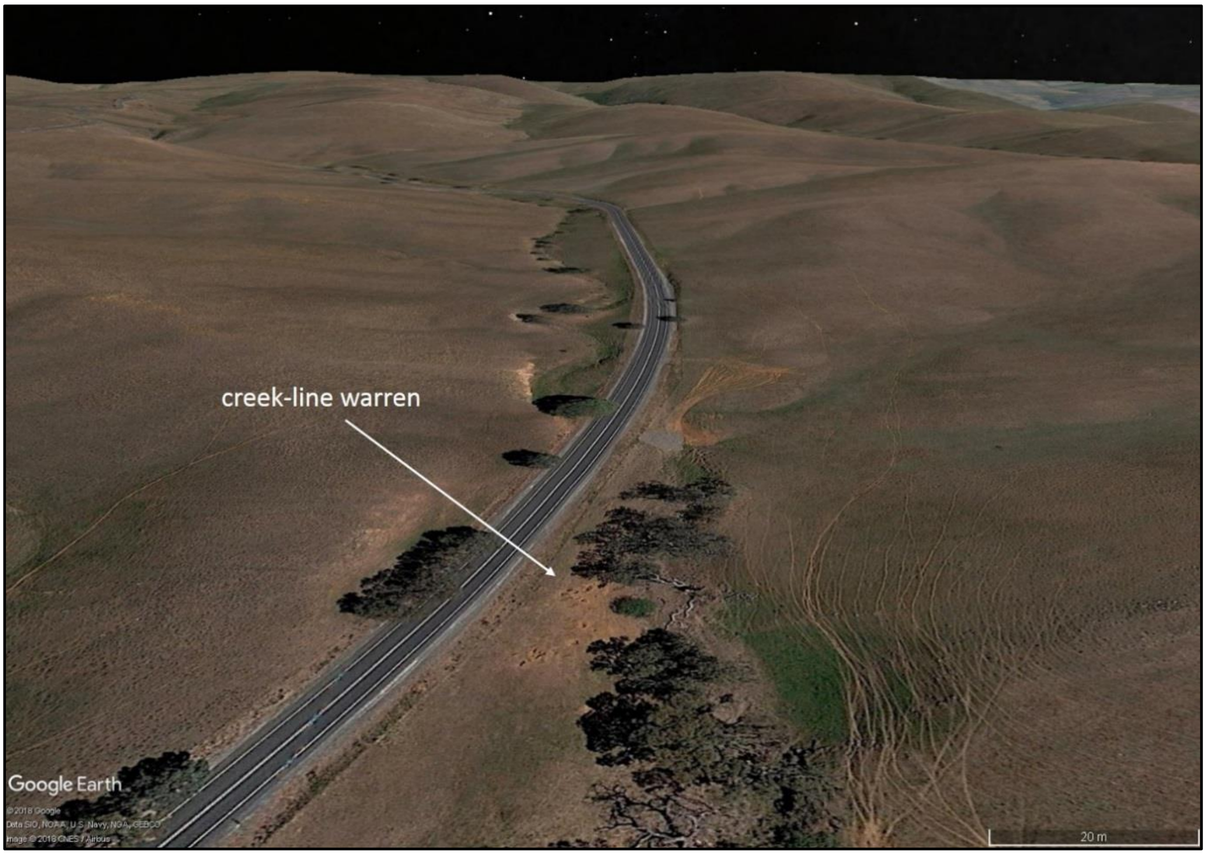


*Figure 23: Although wombat warrens are generally restricted to flat terrain, they can also be found in the eastern foothills of the Mt Lofty Ranges along the edges of creeks, such as this warren alongside the Stott Highway to the north-west of Sedan (source: Google Earth 7.3.2.5487, DigitalGlobe 3-D image, -34.554579 139.233880, accessed 5 August 2018).*

*Association rules analysis*

The top 30 rules for both the level one and level two analyses, which show the overall importance of each variable, are shown in Appendix 1. The highest ranked rules by lift for each level, both of which predict absence, are shown at Table 2.

*Table 2: Highest ranked rule for each level of analysis.*

| Level | Condition | Prediction | Lift | Confidence (%) |
|---|---|---|---|---|
| 1 | Mean annual rainfall: ≤ 227 mm<br>Index of winter rainfall variability: 1.18 - 1.58<br>Aridity index: .17 - .24 | Absence | 1.94 | 66.52 |
| **2** | Land-use: Cereal crops<br>Vegetation: Cleared, non-native vegetation | Absence | 2.11 | 86.93 |

By comparing the rules which predict presence with those that predict absence, we were able to isolate those variables which, when the scale or category of the variable changed, the predicted outcome changed from 'presence' to 'absence', even when none of the other variables in the rule changed. A full list of these variables, with the associated factor influencing the outcome, is shown at Table 3.

*Table 3: Individual variables which have a marked influence on the likelihood that southern hairy-nosed wombats will be absent from the landscape (i.e. reduced abundance).*

| **Variable** | **Factors likely to increase the likelihood of wombats being absent** |
|---|---|
| Mean annual rainfall | ≤ 227 mm (level 1); ≤ 247 mm (level 2) |
| Index of winter rainfall variability | > 1.18 |
| Mean annual temperature | No noticeable effect |
| Aridity index | ≤ .19 |
| Soil clay content | ≤ 18.27% |
| Vegetation sub-groups | Mallee with a dense shrubby understory |
| Land-use | Cereal crops |

The environmental variables which have the greatest influence on determining whether wombats are present or absent, when taken in context with other variables except land-use, are rainfall and rainfall variability. Rainfall is a determining factor in 80% of the level one rules (60 / 75), with the 26 highest ranked rules all predicting that wombats are less likely to be present when the mean rainfall ≤ 227 mm / annum (lift = up to 1.94, confidence = up to 66.54%), even when other factors such as vegetation or soil conditions are favourable. A change in rainfall from ≤ 227 mm / annum to > 227 mm / annum altered the predicted outcome from absence (lift = 1.77) to presence (lift = 1.35), indicating that rainfall at that level is an important factor which determines whether or not wombats are likely to be present (Table 4). There was a slight difference in the amount of rainfall which predicted absence between the level one (≤ 227 mm) and level two (≤ 247 mm).

Soil clay content is also an important variable, as wombats are more likely to be absent in areas with low soil clay content (level two rule # 6, absence, soil clay content = 11.07 - 18.27%, lift = 1.94, confidence = 78.97%), even when other variables are favourable (index of winter rainfall variability: 0.79 - 1.18, aridity index: .19 - .28).

*Table 4: An example of two rules from the level one analysis highlighting how a change in one variable (mean annual rainfall) can change the predicted outcome, even when the other variables remain unchanged.*

| Rule | Variables | Prediction | Lift | Confidence (%) |
|---|---|---|---|---|
| **12** | Mean annual rainfall: ≤ 227 mm<br>Aridity index: .17 - .24<br>Mean annual temperature: 17.09 - 18.27°C<br>Soil clay content: 20.63 - 27.05%<br>Vegetation: Saltbush and bluebush shrublands | Absence | 1.77 | 60.40 |
| **29** | Mean annual rainfall: 227 - 300 mm<br>Aridity index: .17 - .24<br>Mean annual temperature: 17.09 - 18.27°C<br>Soil clay content: 20.63 - 27.05%<br>Vegetation: Saltbush and bluebush shrublands | Presence | 1.35 | 88.98 |

The four highest ranked rules from the level two analysis, all of which predicted absence, contained the variable 'Land-use: Cereal crops' (lift = 2.06 – 2.11, confidence = 84.91 - 86.93%). Rules 5 – 8 predicted absence based on 'Soil clay content: 11.07 - 18.27% (lift = 1.87 – 1.92, confidence = 77.06 – 78.97%), and rules 9 – 10 predicted absence based on 'Vegetation class: Mallee with a shrubby understory' (lift = 1.80, confidence = 74.29 – 74.33%). The highest ranked rule predicting presence in the level two analysis included the variable 'Mean annual rainfall: 247 – 340 mm' (Appendix 1 Table 2)

## Discussion

The results of this study suggest that there are several key factors which influence the distribution and abundance of southern hairy-nosed wombats at different spatial scales. At the species-wide level, the distribution appears to be constrained by climate variables, especially rainfall and rainfall variability. At the regional / local level, the main influences on the fragmentary and patchy nature of the wombat distribution appears to be land-use, soil texture, and vegetation type.

Conceptually, although southern hairy-nosed wombats do not currently occur in regions where the mean annual temperature is > 19.45°C, the direct effects of temperature are unlikely to be the major factor affecting their distribution and / or abundance. Southern hairy-nosed wombats possess a range of physiological and behavioural adaptions which allow them to survive in a hot, arid environment. As wombats are both nocturnal and fossorial, they can protect themselves from the extremes of temperatures of the Australian outback by remaining within their burrows during periods of intense heat or cold (Wells 1978; Shimmin *et al.* 2002). This is confirmed by the association rules analysis, which did not find a temperature effect on presence / absence (Table 3).

Wombats have one of the lowest water flux rates (the ratio between water intake and water loss) of any mammal; ~ 25% of that for a similarly sized eutherian mammal (Evans *et al.* 2003). This allows them to survive without the need to have access to free water for drinking. They can also maintain their energy balance during poor growing seasons by reducing their field metabolic rate (FMR) to about half that of a good season. Because of these adaptions, the effects of rainfall on the species-wide distribution and abundance of southern hairy-nosed wombats are likely to be more complex than just the direct impacts. As wombats obtain most of their water from the plants they eat, the effects of precipitation on vegetation communities and plant water holding capacity are likely to be important (Reisinger *et al.* 2014). While adult wombats are generally able to survive dry seasons, reproduction and recruitment can be severely affected by drought (i.e. rainfall variability) (Gaughwin *et al.* 1998; McGregor and Wells 1998). Therefore, we hypothesise that while wombats may be present in areas of low rainfall and high rainfall variability, the effects of these extremes on recruitment are likely to have an impact on abundance; and our results provide evidence to support this.

Wombats are not present in areas where the mean annual rainfall is < 154 mm / annum, the aridity index is < 0.10 (arid), or the index of winter rainfall variability is > 2.0 (extreme). Although these indices represent the limits of the distribution, the population density close to these extremes is at much lower levels than it is in the core parts of the range. Wombats are more likely to be absent from areas where the mean annual rainfall is ≤ 227 mm / annum, even when other variables such as vegetation (saltbush and bluebush shrublands) and soil clay content are favourable. This phenomenon can be observed in the largest wombat population group on the Nullarbor Plain, where the population density declines markedly in areas where the mean annual rainfall is < 227 mm (Figure 24).

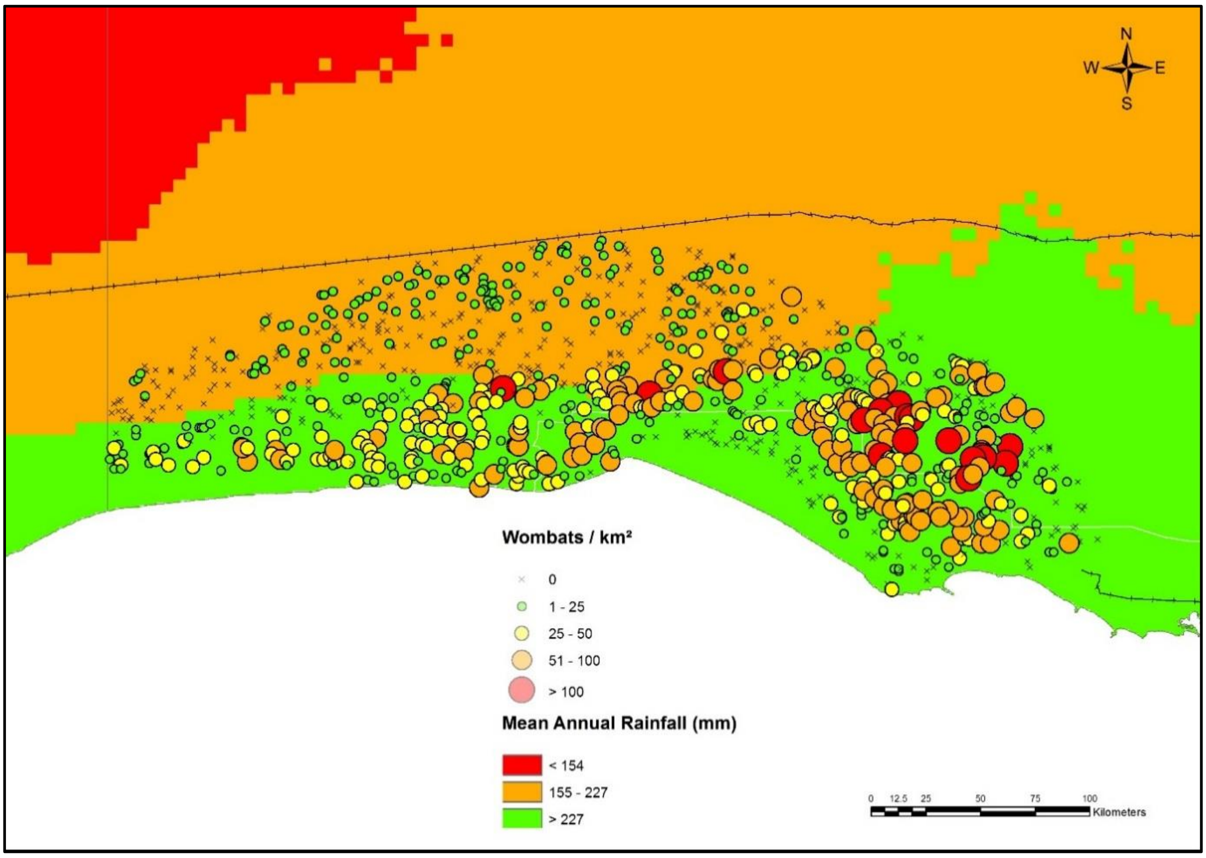


*Figure 24: Rainfall map of the Nullarbor Plain wombat population group showing the effect of rainfall on abundance. The highest population density occurs in areas where the mean annual rainfall is > 227mm, with a significantly lower abundances in areas between 154 – 227 mm / annum.*

This effect of rainfall on population abundance has implications for wombats under the on-going influences of anthropogenic climate change. Although there is uncertainty in the predictions regarding potential changes in annual rainfall, there is general agreement that drought frequency and rainfall variability – especially during winter and spring – are likely to increase (Reisinger *et al.* 2014). This is important, as the association rules analysis also identified rainfall variability as a major factor influencing wombat presence or absence (56% of the rules generated), with an index of 1.18 (moderate – high) being the 'boundary' between an increased likelihood of presence and absence (see level one rules # 23 and 30: Appendix 1 *Table 1*). This suggests that the effects of anthropogenic climate change on rainfall variability and drought frequency are likely to have a negative impact on wombat abundance by reducing breeding and recruitment.

As southern hairy-nosed wombats are fossorial animals, regolith and soil also play key roles in their distribution and abundance, and soil type is thought to have an effect on the social structure of the wombat population (Walker *et al.* 2007). Although our results found that the distribution of southern hairy-nosed wombats is largely restricted to calcareous regolith and soils, and previous studies have shown that the majority of the wombat distribution occurs in areas where the carbonate ($CaCO3$) content of the regolith is > 90% (Marshall *et al.* 2017), whether this is an environmental limitation on wombats per se or just a non-causal correlation cannot be directly inferred from the data. One potential clue to resolve this lies in examining both the former distribution of southern hairy-nosed wombats and the current and former distribution of the closely related northern hairy-nosed wombat.

Although southern hairy-nosed wombats currently do not occur to the east of Morgan on the north-west bend in the Murray River, at the time of European settlement they could be found along the northern banks of the river for a further 250 km to Euston in NSW. And while the last surviving remnant population of the closely related northern hairy-nosed wombat is in the Epping Forest National Park in central Queensland, at the time of European settlement their Queensland distribution extended southwards to St George on the NSW border, and there was a large population near Jerilderie in the Riverina district (Swinbourne *et al.* 2017). None of these areas are dominated by calcareous regolith or soils – with all three areas being mainly vertosols and chromosols layered over 'Belyando and 'Murray' regoliths, which have a carbonate content of < 50% (Dart *et al.* 2007). Further, southern hairy-nosed wombats currently occur in a number of regions where the carbonate content of the soil is < 90%, especially around Lake Acraman in the southern area of the Gawler Ranges / Lake Harris region (Figure 10). This suggests that, while the soil must be capable of supporting the warren structure and of providing the microenvironment that wombats require to conserve energy and water, calcareous soils high in carbonate content do not appear to be an environmental necessity for wombats.

But the disappearance of southern hairy-nosed wombats from parts of their former distribution in the late nineteenth / early twentieth centuries, and their persistence in areas dominated by calcrete limestone such as the river flats of the Murray River between Blanchetown and Swan Reach in the Murraylands (Swinbourne *et al.* 2017), suggests that these areas of this type might act as important refugia. There appears to be little doubt that the disappearance of southern hairy-nosed wombats from much of their former distribution was caused by human persecution, mainly the destruction of warrens to control rabbits and to develop the land for agriculture.

However, the destruction of calcrete warrens is much more difficult than those which have been constructed in loamy or sandy soils due to the hardness of the overtopping layers of calcrete limestone (Steele and Temple-Smith 1998), and this may have allowed wombats to persist in these areas.

While soil type does not appear to have a causal relationship with wombat distribution, soil texture does. Our results suggest that wombats do not occur in locations where the clay content of the soil is outside the range of 9 - 40%, with most (90%) occurring within the range of 16 - 28%. This is most likely related to the stability of the warren (Laundré and Reynolds 1993), with soils with low clay content (and high sand content) being too friable and prone to collapse. Evidence for this can be seen in the gap in the protected area between the Nullarbor Plain and Gawler Ranges population groups (Yellabinna Regional Reserve). This area is dominated by a series of vegetated sand-dunes which have soils which are high in sand and low in clay content (< 10%). As a result, wombats are completely absent despite being in high numbers right up to the edges of the dunefields (Figure 25). At the other end of the spectrum, soils with high clay content are likely to be too difficult to dig, especially when dry and hard, and they would retain too much moisture, which would have an adverse effect on the burrow microclimate (Reichman and Smith 1990).

The distribution and local area abundance of southern hairy-nosed wombats is also influenced by vegetation. Hairy-nosed wombats have long been thought to favour open grassland to woodland – having once being described as 'plains wombats'(Australian Town and Country Journal 1885), and landholders have consistently claimed that land clearing for grazing has the effect of increasing wombat numbers by removing unfavourable habitat, especially mallee woodlands (Stott 1998). The evidence suggests that this claim is valid, with a greater occupancy rate in open vegetation classes (saltbush and bluebush shrublands, cleared non-native vegetation) than in closed vegetation classes (mallee with dense shrubby understory, lift = 1.36 – 1.80, confidence = 46.36 – 74.33%). This effect is apparent on the Nullarbor Plain in the vicinity of the Yalata Aboriginal Community. Although the wombat population density to the north and east of Yalata is amongst the highest across the species-wide distribution, they are virtually absent from the mallee areas to the south (Figure 26)

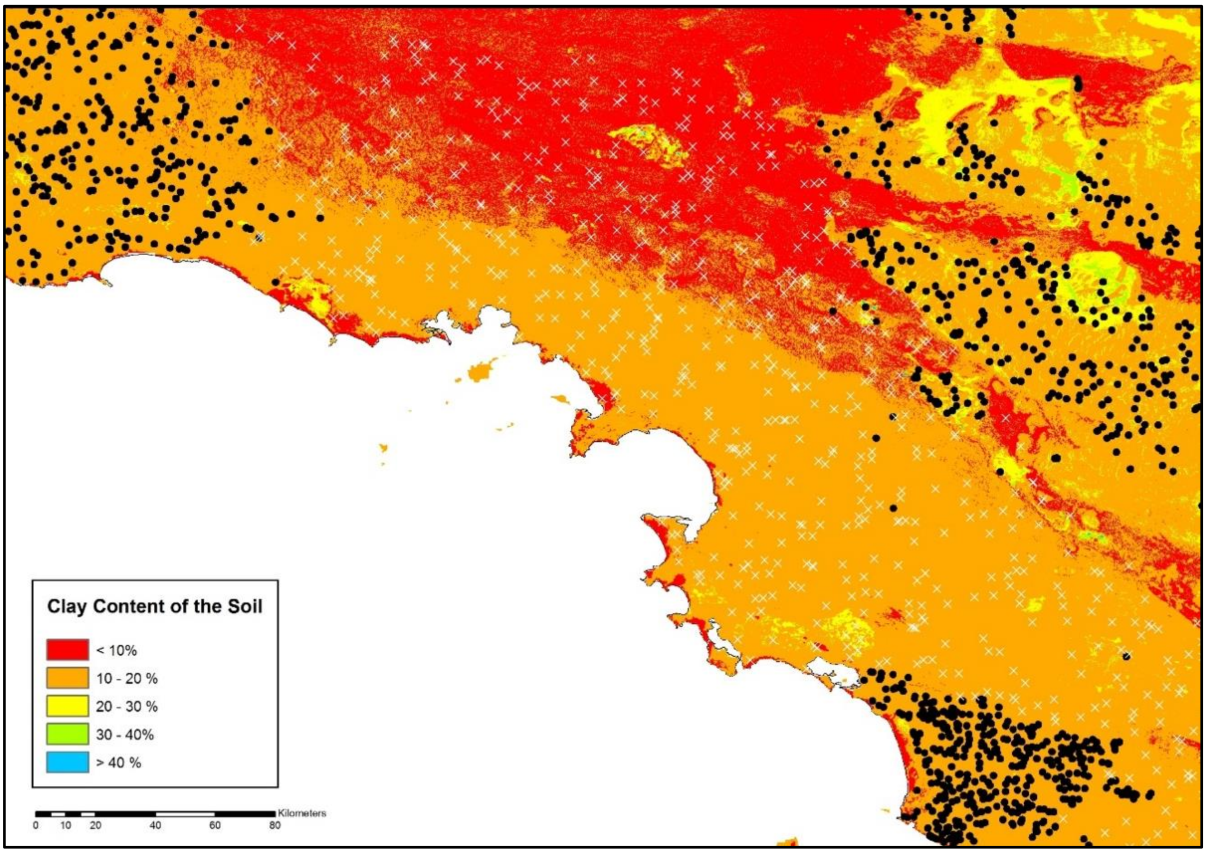


*Figure 25: Map showing the clay content of the soil in the region between the Nullarbor (black dots on the top left of image), Gawler Ranges (top right) and Eyre Peninsula (bottom right) wombat populations. Note how wombats are absent (white crosses) from areas where the clay content of the soil is < 10% (red areas). The gap in the distribution along the coast in favourable soil can be explained by land-use practices (see Figure 28).*

Vegetation is also a factor which explains the constraints on the western edge of the species-wide distribution. Although the current western edge of the wombat distribution is near Caiguna in Western Australia, at the time of European settlement wombats could be found as far west as Balladonia, a further 120 km to the west (Swinbourne *et al.* 2017). The reason why they did not extend any further is because the area to the west of Balladonia is dominated by mallee woodlands with dense shrubby understory and the steep terrain of the Fraser Range; and these factors constrain any potential westward population expansion today.

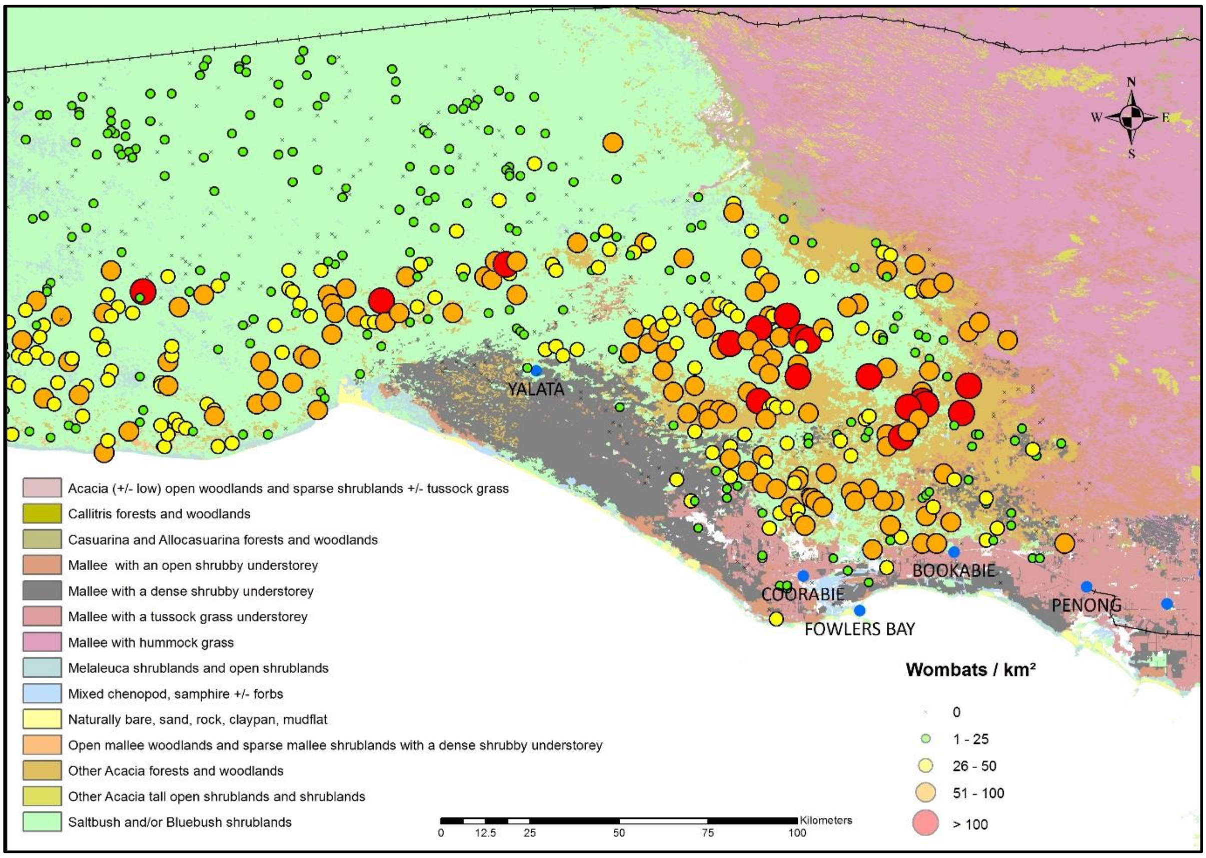


*Figure 26: Vegetation map of the eastern edge of the Nullarbor Plain population group, showing the effect of vegetation type on wombat abundance. Note how the abundance is high to the north and east of Yalata in open vegetation types (green = saltbush and / or bluebush shrublands, brown = open acacia woodlands), but wombats are almost completely absent to the south in the closed vegetation communities (grey = mallee with dense scrubby understory).*

While environmental variables such as climate, soil and vegetation play important roles in wombat distribution, the over-riding factor which influences the fragmentary nature of the southern hairy-nosed wombat distribution is anthropogenic land-use practice, with there being an inverse relationship between the intensity of land-use and the abundance of wombats (cereal crops: lift = 2.22, confidence = 86.93%). Surveys of landholders have consistently found that the presence of wombats is generally tolerated on grazing land, except when they cause damage to infrastructure. However, landholders will take strong action to remove wombats from croplands (Stott 1998; Sparrow *et al.* 2011; Sparrow 2013) (Figure 27).

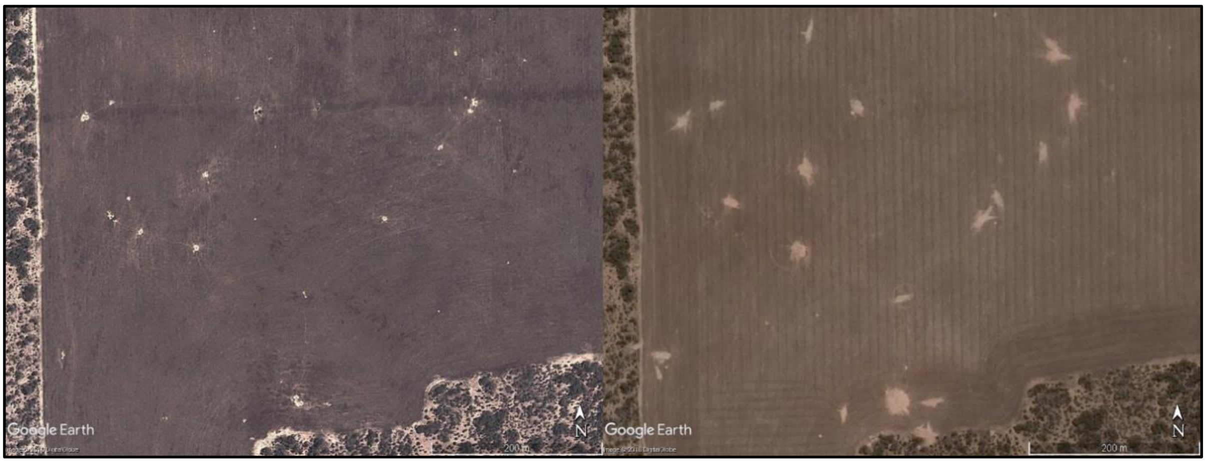


*Figure 27: Two satellite images showing landholder action on the presence of wombats on agricultural land. In the left image, from 2009, there are a number of warrens present in a paddock used for grazing. By the time of the right image (2015), the land-use practice has been changed to cropping, and as a consequence all the warrens have been destroyed by the landholder (source: Google Earth 7.3.2.5487. DigitalGlobe / CNES/Airbus -31.817973 132.934501, accessed 9 August 2018).*

This effect is most apparent in the area between the Nullarbor Plain and Eyre Peninsula population groups. This area was occupied by wombats at the time of European settlement (Swinbourne *et al.* 2017) and the population groups were most likely contiguous. However, there are no wombats in this area today apart from a few isolated colonies surviving on favourable habitat; which lends support to the idea that they were once more widespread in the region (Figure 28). This is similar to the situation which caused the decline and near extinction of wombats from the Yorke Peninsula. While wombats could once be found in large numbers over much of the peninsula, the opening of the land for agriculture in the nineteenth century resulted in a dedicated campaign to remove them (Kadina and Wallaroo Times 1925); a situation which continues to this day (Sparrow 2010).

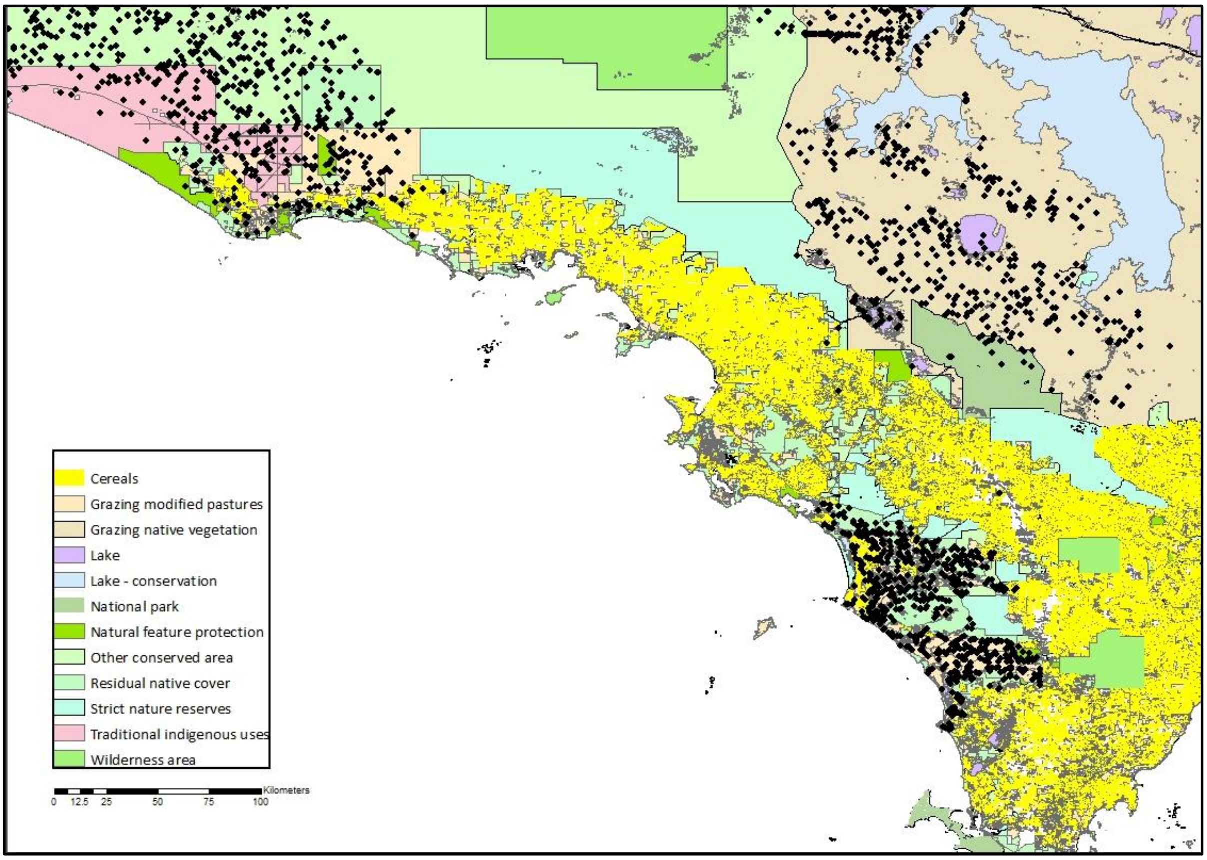


*Figure 28: Map showing the effect of agricultural land-use practices on the distribution of southern hairy-nosed wombats population groups in the western region of South Australia: Nullarbor (black dots on the top left of image), Gawler Ranges (top right) and Eyre Peninsula (bottom right). Note how wombats are generally absent from areas where the main land-use is cropping agriculture (yellow areas) but are present on grazing land (light pink).*

The differences between how wombats are tolerated on grazing and croplands raises an interesting possibility with regard to potential changes in the distribution of southern hairy-nosed wombats in response to anthropogenic climate change. Given the dominance of land-use as a determinant of wombat distribution, if changing temperatures or rainfall patterns were to drive changes in land-use patterns, this may have an indirect impact on the distribution and abundance of southern hairy-nosed wombats. The eastern edge of the Nullarbor Plains population group is where much of the human-wombat conflict currently occurs (Sparrow 2013) due to the high population densities of wombats along the boundary between protected areas, grazing and croplands. If climate change were to cause these areas to become less favourable for cropping by reducing crop yields - which is predicted by most climate change models (Luo *et al.* 2005; Challinor *et al.* 2014) - and result in a shift in farming practices from cropping to grazing, this might favour wombats by reducing unfavourable and increasing favourable land-use practices. As this goes to the core of much of the concerns which are expressed about the wombat population, more research is recommended in this area.

In addition to the factors presented here, there are likely to be other variables that influence wombat distribution and abundance that we have not been able to model due to a lack of available data. These include the decline in native pasture and the spread of invasive weed species and toxic plants (Lenz and Facelli 2005; Woolford *et al.* 2014), and exotic diseases or parasites (Ruykys *et al.* 2013).

One effect that we did observe, but were unable to model in detail, is the effect of local area topography on soil, water and vegetation. On the Nullarbor Plain and in Western Australia we noted large, densely populated colonies of wombat warrens clustered in claypan depressions, with few warrens on the slightly higher ground in-between (Figure 29). During both our ground surveys and the analysis of the satellite imagery we noticed that these depressions were strong predictors for warren locations, with warrens often being concentrated around the edges of the claypan. This phenomenon has been previously described by other researchers undertaking surveys of the region (Aitken 1973; Löffler and Margules 1980; St.John and Saunders 1989). Much of the Nullarbor Plain consists of a mosaic of these claypan depressions, which were formed by colluvial in-filling (Mitchell *et al.* 1979). We therefore recommend further research be undertaken to map these features in detail and to correlate the maps produced with wombat presence / absence data.

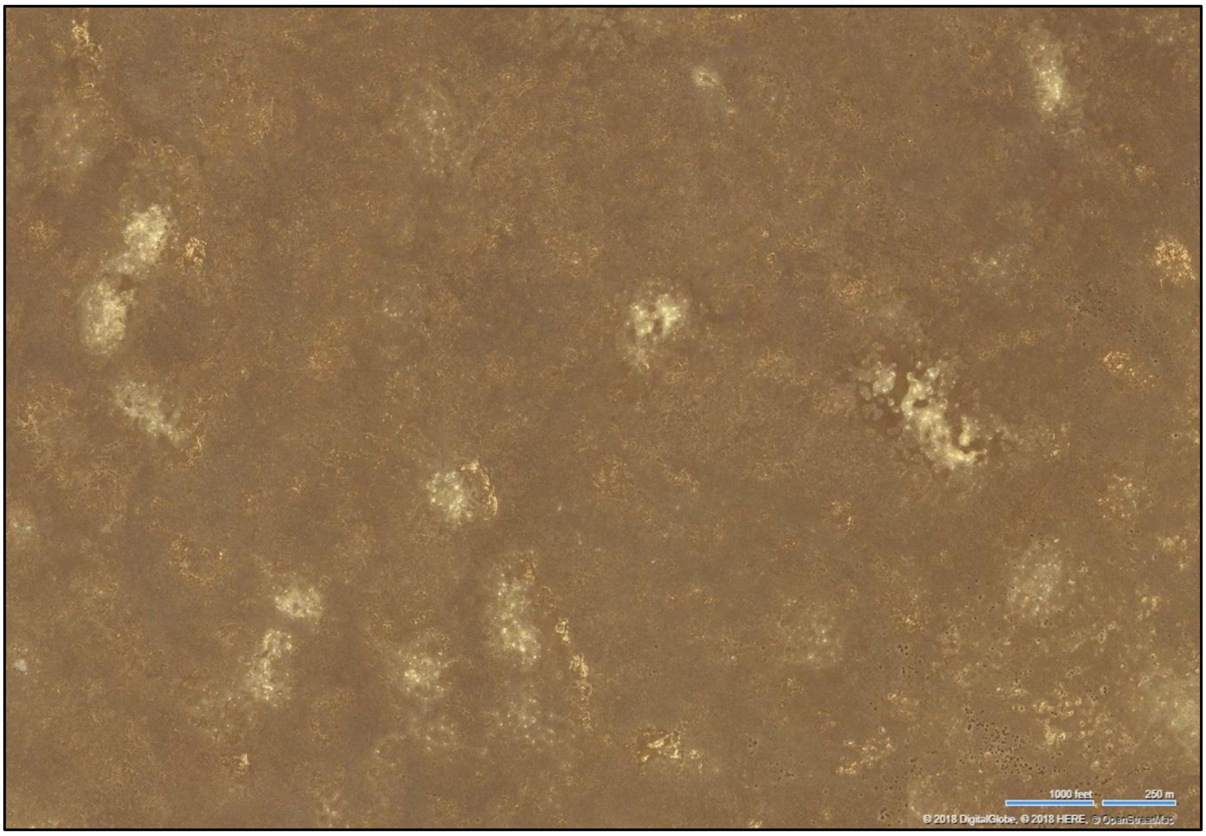


*Figure 29: Satellite image of the Nullarbor Plains region ~ 100 km to the east of the Western Australia border in the Nullarbor Wilderness Protection Area showing the effect of terrain and soil on local area distribution and abundance. Each light area in the image is a cluster of wombat warrens covering up to 16 ha. and containing up to 50 warrens (equivalent to 300 warrens / km$^2$). All these clusters are located in claypan depressions, with few warrens on the high points in between (source: Bing Maps on-line, DigitalGlobe -31.312297 130.074260, accessed 25 October 2018).*

Another likely factor is the influence of grazing competition. Approximately half of the wombat distribution in South Australia and almost all of the distribution in Western Australia is located on grazing land; predominantly rangeland sheep grazing. Competition from livestock is likely to have an effect on wombat abundance, but there is no definitive research which quantifies this. Similarly, the effect of resource competition from other herbivores such as kangaroos and Mediterranean snails (*Cernuella virgata*, *Cochlicella acuta* and *Theba pisana*), which are significant pest species throughout the Murraylands and Eyre and Yorke Peninsula regions (Baker 1998), have not been quantified, and we recommend research be undertaken in this area.

The effects of predation may also have in impact on wombat abundance. While there are several predators that could potentially prey on wombats to a limited extent, including the wedge-tailed eagle (*Aquila audax*), southern carpet python (*Morelia spilota imbricata*) and feral species such as the red fox (*Vulpes vulpes*) and cat (*Felis catus*), the only predator which is thought to have any real impact on the southern hairy-nosed wombat is the dingo (*Canis lupus dingo*). Although there have been suggestions that the presence of dingoes acts as a deterrent to wombats, and that the population density is lower in areas outside the dingo fence as a result (Sparrow 2013), there is no firm evidence to support this. Indeed, the density of warrens outside the dingo fence on the Nullarbor Plain is higher than in any other part of the wombat distribution, and the wombat population appears to be increasing and expanding in this area. Consequently, as such a large proportion of the wombat population is located outside the dingo fence, we recommend research to quantify the relationship between wombats and dingoes.

Finally, an important point to note about the southern hairy-nosed wombat distribution is that in some areas it has been expanding geographically for the past few decades. In the Gawler Ranges the population has been expanding northwards at an average rate of ~ 1.5 km per year since at least 1988 (Swinbourne *et al.* 2018a). On the Nullarbor, wombats now occupy areas to the north and west of the distribution that was described in the 1970s and 80s, and in Western Australia most landholders believe that wombats have also been expanding both northwards and westwards (B. Campbell, pers. comm.). Although some people suggest that this represents wombats moving into new areas (Stott 1998; Sparrow *et al.* 2011), an alternate explanation is that they are reoccupying areas that were lost as a result of past agricultural practices and competition from introduced species, especially rabbits (Swinbourne *et al.* 2017). In either case, the expanding distribution may not have reached its maximum extent or fundamental environmental niche, and the realised niche that wombats currently occupy may not represent the full range of environmental variables that predict their potential distribution (Thuiller *et al.* 2004). Therefore, we should be cautious about assuming whether the calculated limits on their distribution based on climatological factors presented here are due to actual limits, or whether they simply represent the current boundaries.

## Conclusion

As is the case for most species, climate is an important factor which constrains the species-wide distribution of southern hairy-nosed wombats, with rainfall and winter rainfall variability appearing to be the most important variables. A mean annual rainfall of 154 mm / annum represents the current limit of the wombat distribution, with local area abundance reducing in areas where the mean annual rainfall is < 227 – 247 mm.

At the regional / local scale, soil texture and vegetation type are important determinants affecting both distribution and abundance. As a fossorial species, wombats are unable to construct and maintain burrows in soils which are too hard or too friable, and it appears that soil clay content of between 9 – 40% represents the limits of habitation, with 16 – 28% being preferred. But while soil texture appears to be a determining factor, soil type does not. Although the majority of the wombat population can be found in areas of calcareous regoliths and soils, this appears to be incidental only, and any soil type which is capable of supporting the warren structure and of providing the necessary burrow micro-climate is like to be suitable.

Wombats also prefer to dig their burrows in open vegetation classes, with the majority of the population being located in saltbush / bluebush shrublands or areas of cleared grasslands. While wombats can also be found in areas of woodlands with dense scrubby understory, especially mallee woodlands, these areas are not preferred, and population abundance in these areas is at much lower levels than in open country. These two factors – soil and vegetation – were the main natural determinants which, along with terrain, shaped the pre-European distribution and local area abundance; constraining the population from spreading further west and preventing the groups on either side of Spencer Gulf from joining across the head of the gulf.

The most important factor which over-rides all other considerations, and which is largely responsible for the fragmentation of the wombat population into regional sub-population groups today, is anthropogenic land-use practice. Although wombats inhabit a range of anthropogenically modified land-use types, including livestock grazing on both rangelands and improved pastures, they are almost completely absent from croplands. The culling of wombats and the destruction of their warrens to open the country for cropland farming is the reason why wombats are almost extinct in the Mid-north and Yorke Peninsula and why they have disappeared from much of the Eyre Peninsula and Far West Coast of South Australia.

Notwithstanding the analysis we have presented here on the factors affecting wombat distribution and abundance, there remains several important areas that we have not been able to model due to a lack of available data. We therefore recommend further research to determine the effects of grazing competition from livestock and other native and pest species (e.g. kangaroos and Mediterranean snails) on wombat abundance, and to characterise the relationship between wombats and dingoes. We also recommend research to determine whether the apparent environmental limits on wombat distribution represent the actual limits, or whether a population which is currently expanding may still spread beyond the predicted limits.

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# Appendix 1 to Chapter 9: Association Rules Tables

*Table 1: Level 1 Association Rules, including all regions where southern hairy-nosed wombats can be found, but excluding land-use data (top 30 rules shown).*

| Rank | Condition | Prediction | Lift | Condition Support (%) | Confidence (%) | Rule Support (%) | Deployability (%) |
|---|---|---|---|---|---|---|---|
| **1** | Mean annual rainfall: ≤ 227 mm<br>Index of winter rainfall variability: 1.18 - 1.58<br>Aridity index: .17 - .24 | Absence | 1.94 | 8.45 | 66.52 | 5.62 | 2.83 |
| **2** | Mean annual rainfall: ≤ 227 mm<br>Index of winter rainfall variability: 1.18 - 1.58<br>Aridity index: .17 - .24<br>Mean annual temperature: 17.09 - 18.27°C | Absence | 1.94 | 8.45 | 66.52 | 5.62 | 2.83 |
| **3** | Mean annual rainfall: ≤ 227 mm<br>Index of winter rainfall variability: 1.18 - 1.58<br>Aridity index: .17 - .24<br>Soil clay content: 20.63 - 27.05% | Absence | 1.94 | 7.90 | 66.20 | 5.23 | 2.67 |
| **4** | Mean annual rainfall: ≤ 227 mm<br>Index of winter rainfall variability: 1.18 - 1.58<br>Aridity index: .17 - .24<br>Mean annual temperature: 17.09 - 18.27°C<br>Soil clay content: 20.63 - 27.05% | Absence | 1.94 | 7.90 | 66.20 | 5.23 | 2.67 |

| Rank | Condition | Prediction | Lift | Condition Support (%) | Confidence (%) | Rule Support (%) | Deployability (%) |
|---|---|---|---|---|---|---|---|
| **5** | Mean annual rainfall: ≤ 227 mm<br>Index of winter rainfall variability: 1.18 - 1.58<br>Mean annual temperature: 17.09 - 18.27°C<br>Soil clay content: 20.63 - 27.05%<br>Vegetation: Saltbush and bluebush shrublands | Absence | 1.92 | 9.42 | 65.54 | 6.17 | 3.25 |
| **6** | Mean annual rainfall: ≤ 227 mm<br>Index of winter rainfall variability: 1.18 - 1.58<br>Mean annual temperature: 17.09 - 18.27°C<br>Vegetation: Saltbush and bluebush shrublands | Absence | 1.85 | 12.08 | 63.34 | 7.65 | 4.43 |
| **7** | Mean annual rainfall: ≤ 227 mm<br>Index of winter rainfall variability: 1.18 - 1.58<br>Mean annual temperature: 17.09 - 18.27°C<br>Soil clay content: 20.63 - 27.05% | Absence | 1.83 | 11.33 | 62.43 | 7.07 | 4.26 |
| **8** | Mean annual rainfall: ≤ 227 mm<br>Mean annual temperature: 17.09 - 18.27°C<br>Index of winter rainfall variability: 1.18 - 1.58 | Absence | 1.79 | 14.69 | 61.31 | 9.00 | 5.68 |
| **9** | Mean annual rainfall: ≤ 227 mm<br>Aridity index: .17 - .24<br>Vegetation: Saltbush and bluebush shrublands | Absence | 1.78 | 9.23 | 60.93 | 5.62 | 3.60 |

| Rank | Condition | Prediction | Lift | Condition Support (%) | Confidence (%) | Rule Support (%) | Deployability (%) |
|---|---|---|---|---|---|---|---|
| **10** | Mean annual rainfall: ≤ 227 mm<br>Mean annual temperature: 17.09 - 18.27°C<br>Aridity index: .17 - .24<br>Vegetation: Saltbush and bluebush shrublands | Absence | 1.77 | 9.04 | 60.68 | 5.49 | 3.55 |
| **11** | Mean annual rainfall: ≤ 227 mm<br>Aridity index: .17 - .24<br>Soil clay content: 20.63 - 27.05%<br>Vegetation: Saltbush and bluebush shrublands | Absence | 1.77 | 8.61 | 60.57 | 5.22 | 3.39 |
| **12** | Mean annual rainfall: ≤ 227 mm<br>Mean annual temperature: 17.09 - 18.27°C<br>Aridity index: .17 - .24<br>Soil clay content: 20.63 - 27.05%<br>Vegetation: Saltbush and bluebush shrublands | Absence | 1.77 | 8.57 | 60.40 | 5.18 | 3.39 |
| **13** | Mean annual rainfall: ≤ 227 mm<br>Aridity index: .17 - .24 | Absence | 1.74 | 10.87 | 59.39 | 6.46 | 4.42 |
| **14** | Mean annual rainfall: ≤ 227 mm<br>Aridity index: .17 - .24<br>Mean annual temperature: 17.09 - 18.27°C | Absence | 1.73 | 10.69 | 59.15 | 6.32 | 4.37 |
| **15** | Mean annual rainfall: ≤ 227 mm<br>Aridity index: .17 - .24<br>Soil clay content: 20.63 - 27.05% | Absence | 1.72 | 10.11 | 58.76 | 5.94 | 4.17 |

| Rank | Condition | Prediction | Lift | Condition Support (%) | Confidence (%) | Rule Support (%) | Deployability (%) |
|---|---|---|---|---|---|---|---|
| **16** | Mean annual rainfall: ≤ 227 mm<br>Aridity index: .17 - .24<br>Mean annual temperature: 17.09 - 18.27°C<br>Soil clay content: 20.63 - 27.05% | Absence | 1.71 | 10.07 | 58.61 | 5.90 | 4.17 |
| **17** | Mean annual rainfall: ≤ 227 mm<br>Index of winter rainfall variability: 1.18 - 1.58<br>Soil clay content: 20.63 - 27.05%<br>Vegetation: Saltbush and bluebush shrublands | Absence | 1.70 | 11.27 | 58.08 | 6.54 | 4.72 |
| **18** | Mean annual rainfall: ≤ 227 mm<br>Index of winter rainfall variability: 1.18 - 1.58<br>Vegetation: Saltbush and bluebush shrublands | Absence | 1.62 | 15.89 | 55.26 | 8.78 | 7.11 |
| **19** | Mean annual rainfall: ≤ 227 mm<br>Mean annual temperature: 17.09 - 18.27°C<br>Soil clay content: 20.63 - 27.05%<br>Vegetation: Saltbush and bluebush shrublands | Absence | 1.52 | 14.96 | 51.89 | 7.76 | 7.20 |
| **20** | Mean annual rainfall: ≤ 227 mm<br>Index of winter rainfall variability: 1.18 - 1.58<br>Soil clay content: 20.63 - 27.05% | Absence | 1.50 | 15.13 | 51.38 | 7.77 | 7.36 |
| **21** | Mean annual rainfall: ≤ 227 mm<br>Mean annual temperature: 17.09 - 18.27°C<br>Soil clay content: 20.63 - 27.05% | Absence | 1.46 | 18.22 | 49.83 | 9.08 | 9.14 |

| Rank | Condition | Prediction | Lift | Condition Support (%) | Confidence (%) | Rule Support (%) | Deployability (%) |
|---|---|---|---|---|---|---|---|
| **22** | Mean annual rainfall: ≤ 227 mm<br>Mean annual temperature: 17.09 - 18.27°C<br>Vegetation: Saltbush and bluebush shrublands | Absence | 1.46 | 20.26 | 49.79 | 10.09 | 10.17 |
| **23** | Mean annual rainfall: ≤ 227 mm<br>Index of winter rainfall variability: 1.18 - 1.58 | Absence | 1.45 | 22.29 | 49.56 | 11.05 | 11.24 |
| **24** | Mean annual rainfall: ≤ 227 mm<br>Mean annual temperature: 17.09 - 18.27°C | Absence | 1.41 | 25.46 | 48.31 | 12.30 | 13.16 |
| **25** | Mean annual rainfall: ≤ 227 mm<br>Soil clay content: 20.63 - 27.05%<br>Vegetation: Saltbush and bluebush shrublands | Absence | 1.40 | 17.21 | 48.03 | 8.27 | 8.94 |
| **26** | Mean annual rainfall: ≤ 227 mm<br>Vegetation: Saltbush and bluebush shrublands | Absence | 1.37 | 26.72 | 46.96 | 12.55 | 14.17 |
| **27** | Mean annual rainfall: 227 - 300 mm<br>Aridity index: .17 - .24<br>Mean annual temperature: 17.09 - 18.27°C<br>Vegetation: Saltbush and bluebush shrublands | Presence | 1.36 | 11.03 | 89.63 | 9.89 | 1.14 |
| **28** | Vegetation: Mallee with a dense shrubby understorey | Absence | 1.36 | 11.14 | 46.36 | 5.17 | 5.98 |
| **29** | Mean annual rainfall: 227 - 300 mm<br>Aridity index: .17 - .24<br>Mean annual temperature: 17.09 - 18.27°C<br>Soil clay content: 20.63 - 27.05%<br>Vegetation: Saltbush and bluebush shrublands | Presence | 1.35 | 7.15 | 88.98 | 6.36 | .79 |

| Rank | Condition | Prediction | Lift | Condition Support (%) | Confidence (%) | Rule Support (%) | Deployability (%) |
|---|---|---|---|---|---|---|---|
| **30** | Mean annual rainfall: 227 - 300 mm<br>Mean annual temperature: 17.09 - 18.27°C<br>Index of winter rainfall variability: 0.79 - 1.18<br>Vegetation: Saltbush and bluebush shrublands | Presence | 1.35 | 7.55 | 88.60 | 6.69 | .86 |

*Table 2: Level 2 Association Rules analysis, including data for land-use categories but excluding the Western Australia population group (top 30 rules shown).*

| Rank | Condition | Prediction | Lift | Condition Support (%) | Confidence (%) | Rule Support (%) | Deployability (%) |
|---|---|---|---|---|---|---|---|
| **1** | Land-use: Cereal crops<br>Vegetation: Cleared, non-native vegetation | Absence | 2.11 | 7.68 | 86.93 | 6.67 | 1.00 |
| **2** | Land-use: Cereal crops<br>Vegetation: Cleared, non-native vegetation<br>Index of winter rainfall variability: 0.79 - 1.18 | Absence | 2.10 | 6.55 | 86.73 | 5.68 | .87 |
| **3** | Land-use: Cereal crops<br>Index of winter rainfall variability: 0.79 - 1.18 | Absence | 2.06 | 7.48 | 84.97 | 6.35 | 1.12 |
| **4** | Land-use: Cereal crops | Absence | 2.06 | 8.77 | 84.91 | 7.45 | 1.32 |
| **5** | Soil clay content: 11.07 - 18.27%<br>Aridity index: .19 - .28 | Absence | 1.92 | 7.82 | 78.97 | 6.18 | 1.65 |
| **6** | Index of winter rainfall variability: 0.79 - 1.18<br>Soil clay content: 11.07 - 18.27%<br>Aridity index: .19 - .28 | Absence | 1.92 | 7.82 | 78.97 | 6.18 | 1.65 |
| **7** | Mean annual rainfall: 247 - 340 mm<br>Soil clay content: 11.07 - 18.27%<br>Aridity index: .19 - .28 | Absence | 1.87 | 6.65 | 77.06 | 5.12 | 1.52 |

| Rank | Condition | Prediction | Lift | Condition Support (%) | Confidence (%) | Rule Support (%) | Deployability (%) |
|---|---|---|---|---|---|---|---|
| **8** | Mean annual rainfall: 247 - 340 mm<br>Index of winter rainfall variability: 0.79 - 1.18<br>Soil clay content: 11.07 - 18.27%<br>Aridity index: .19 - .28 | Absence | 1.87 | 6.65 | 77.06 | 5.12 | 1.52 |
| **9** | Vegetation: Mallee with a dense shrubby understorey | Absence | 1.80 | 8.96 | 74.33 | 6.66 | 2.30 |
| **10** | Vegetation: Mallee with a dense shrubby understorey<br>Index of winter rainfall variability: 0.79 - 1.18 | Absence | 1.80 | 8.01 | 74.29 | 5.95 | 2.06 |
| **11** | Mean annual temperature: 17.09 - 18.27°C<br>Index of winter rainfall variability: 0.79 - 1.18<br>Aridity index: .19 - .28 | Absence | 1.79 | 8.76 | 73.74 | 6.46 | 2.30 |
| **12** | Mean annual temperature: 17.09 - 18.27°C<br>Mean annual rainfall: 247 - 340 mm<br>Index of winter rainfall variability: 0.79 - 1.18<br>Aridity index: .19 - .28 | Absence | 1.76 | 8.31 | 72.46 | 6.02 | 2.29 |
| **13** | Mean annual temperature: 17.09 - 18.27°C<br>Aridity index: .19 - .28 | Absence | 1.76 | 8.96 | 72.39 | 6.49 | 2.47 |
| **14** | Mean annual temperature: 17.09 - 18.27°C<br>Mean annual rainfall: 247 - 340 mm<br>Aridity index: .19 - .28 | Absence | 1.74 | 8.41 | 71.86 | 6.05 | 2.37 |

| Rank | Condition | Prediction | Lift | Condition Support (%) | Confidence (%) | Rule Support (%) | Deployability (%) |
|---|---|---|---|---|---|---|---|
| **15** | Mean annual temperature: 17.09 - 18.27°C<br>Mean annual rainfall: 247 - 340 mm<br>Soil clay content: 18.27 - 25.48%<br>Vegetation: Saltbush and bluebush shrublands<br>Aridity index: ≤ .19 | Presence | 1.69 | 6.34 | 99.16 | 6.29 | .05 |
| **16** | Mean annual temperature: 17.09 - 18.27°C<br>Mean annual rainfall: 247 - 340 mm<br>Soil clay content: 18.27 - 25.48%<br>Vegetation: Saltbush and bluebush shrublands | Presence | 1.68 | 6.69 | 98.60 | 6.59 | .09 |
| **17** | Mean annual rainfall: 247 - 340 mm<br>Soil clay content: 18.27 - 25.48%<br>Vegetation: Saltbush and bluebush shrublands<br>Aridity index: ≤ .19 | Presence | 1.68 | 6.50 | 98.56 | 6.41 | .09 |
| **18** | Mean annual rainfall: 247 - 340 mm<br>Index of winter rainfall variability: 0.79 - 1.18<br>Soil clay content: 11.07 - 18.27% | Absence | 1.66 | 11.49 | 68.22 | 7.84 | 3.65 |
| **19** | Mean annual rainfall: 247 - 340 mm<br>Soil clay content: 18.27 - 25.48%<br>Vegetation: Saltbush and bluebush shrublands | Presence | 1.65 | 7.37 | 96.91 | 7.14 | .23 |

| Rank | Condition | Prediction | Lift | Condition Support (%) | Confidence (%) | Rule Support (%) | Deployability (%) |
|---|---|---|---|---|---|---|---|
| **20** | Mean annual temperature: 17.09 - 18.27°C<br>Mean annual rainfall: 247 - 340 mm<br>Vegetation: Saltbush and bluebush shrublands<br>Aridity index: ≤ .19 | Presence | 1.63 | 9.01 | 95.55 | 8.61 | .40 |
| **21** | Mean annual temperature: 17.09 - 18.27°C<br>Mean annual rainfall: 247 - 340 mm<br>Index of winter rainfall variability: 0.79 - 1.18<br>Soil clay content: 11.07 - 18.27% | Absence | 1.62 | 10.28 | 66.84 | 6.87 | 3.41 |
| **22** | Mean annual temperature: 17.09 - 18.27°C<br>Index of winter rainfall variability: 0.79 - 1.18<br>Soil clay content: 18.27 - 25.48%<br>Vegetation: Saltbush and bluebush shrublands<br>Aridity index: ≤ .19 | Presence | 1.62 | 6.89 | 95.15 | 6.55 | .33 |
| **23** | Mean annual rainfall: 247 - 340 mm<br>Vegetation: Saltbush and bluebush shrublands<br>Aridity index: ≤ .19 | Presence | 1.62 | 9.36 | 95.00 | 8.89 | .47 |
| **24** | Mean annual temperature: 17.09 - 18.27°C<br>Index of winter rainfall variability: 0.79 - 1.18<br>Soil clay content: 18.27 - 25.48%<br>Vegetation: Saltbush and bluebush shrublands | Presence | 1.62 | 7.21 | 94.99 | 6.85 | .36 |

| Rank | Condition | Prediction | Lift | Condition Support (%) | Confidence (%) | Rule Support (%) | Deployability (%) |
|---|---|---|---|---|---|---|---|
| **25** | Mean annual temperature: 17.09 - 18.27°C<br>Mean annual rainfall: 247 - 340 mm<br>Vegetation: Saltbush and bluebush shrublands | Presence | 1.61 | 9.68 | 94.89 | 9.19 | .49 |
| **26** | Vegetation: Cleared, non-native vegetation<br>Aridity index: .19 - .28 | Absence | 1.60 | 9.98 | 65.95 | 6.58 | 3.40 |
| **27** | Index of winter rainfall variability: 0.79 - 1.18<br>Vegetation: Cleared, non-native vegetation<br>Aridity index: .19 - .28 | Absence | 1.60 | 9.98 | 65.95 | 6.58 | 3.40 |
| **28** | Index of winter rainfall variability: 0.79 - 1.18<br>Soil clay content: 18.27 - 25.48%<br>Vegetation: Saltbush and bluebush shrublands<br>Aridity index: ≤ .19 | Presence | 1.60 | 7.17 | 93.84 | 6.73 | .44 |
| **29** | Mean annual temperature: 17.09 - 18.27°C<br>Mean annual rainfall: 247 - 340 mm<br>Index of winter rainfall variability: 0.79 - 1.18<br>Vegetation: Saltbush and bluebush shrublands<br>Aridity index: ≤ .19 | Presence | 1.60 | 5.63 | 93.82 | 5.28 | .35 |
| **30** | Mean annual rainfall: 247 - 340 mm<br>Vegetation: Saltbush and bluebush shrublands | Presence | 1.59 | 10.97 | 93.66 | 10.27 | .70 |

# Chapter 10: Concluding Statement, General Discussion and Future Directions

## General statement

When this research began in 2015 the aims were quite different to those which are evident in the final product. The original scope was focussed on quantifying the ecosystem function of the southern hairy-nosed wombat by examining its impacts on issues such as soil health and species assemblages, and comparing them to the impacts on grazing pressure and land degradation. In other words, we intended to do a cost / benefit analysis of southern hairy-nosed wombats on agricultural land. The idea was to provide the evidence to convince landholders that, rather than seeing wombats as a pest to manage, they would see the financial benefits derived from having an ecosystem engineer to help improve the landscape. If this could be achieved, it might convince landholders to protect wombat numbers from declining further.

This concept was based on two commonly held views, which our research later showed to be incorrect; that 90% of the southern hairy-nosed wombat population lived on agricultural land, and that the population was experiencing an ongoing decline due mainly to anthropogenic factors such as human persecution and habitat loss. Indeed, the International Union for the Conservation of Nature (IUCN) had recently upgraded the conservation status of southern hairy-nosed wombats from 'Least Concern' to 'Near Threatened' (IUCN 2017), which formalised the view that wombat numbers are declining.

In contrast to this assessment, when collecting data during the initial phases of the research on agricultural land across South Australia, nearly every landholder that we spoke to advised us that southern hairy-nosed wombat numbers were not declining, but that they had been increasing for at least the past few decades. This view had been documented in surveys (Sparrow *et al.* 2011), but in general most landholders felt that their voices were being ignored.

This caused a dilemma, because if landholders were of the view that wombat numbers were increasing, they would be unlikely to see the need for, or support, additional conservation measures. As a consequence, we made the decision to change the focus of the research from examining the ecosystem function of southern hairy-nosed wombats to conducting the first species-wide population survey. This research would include developing a reliable means of estimating wombat abundance, and to determine what factors influenced their distribution and abundance at different spatial scales. The objectives of these research tasks were to resolve the disparity in opinions regarding whether the wombat population was growing or declining, and to better understand the environmental and anthropogenic factors which determined why they could be found where they were. Hopefully, this would allow better informed decisions regarding wombat management, whether that be to conserve or control.

**Chapter 1: Introduction: a review of our current understanding of the distribution and abundance of southern hairy-nosed wombats (*Lasiorhinus latifrons*)**

A review of the literature on southern hairy-nosed wombats revealed that we had only a limited understanding of where wombats could be found, how many there might be, whether their numbers were increasing or decreasing, and what factors influenced their population dynamics. This was - in part - because there has never been a species-wide survey of the wombat population. Although there had been an attempt in the 1980s to integrate regional surveys to produce an overall species distribution (St.John and Saunders 1989; St. John 1998), in reality this was just a South Australian survey; no account was made for how many wombats there might be in other states. There had never been any survey of the wombat population in Western Australia, as it was thought that they existed in low numbers in scattered colonies only and that they did not extend very far across the border (Aitken 1973). Since the 1980s there had also been no follow-on surveys in some South Australian regions to establish population trends; most notably the Gawler Ranges, Eyre Peninsula and western areas of the Nullarbor Plain.

As well as revealing our limited understanding of the southern hairy-nosed wombat distribution and abundance, this review also highlighted the need to better understand the landscape factors which determine why wombats can be found where they are, and just as importantly, why they are not found where they aren't. The fragmentary nature of the distribution and the patchy nature of the local area abundance have long been thought to be caused by factors such as land-use and vegetation class. But apart from some personal observations that have been reported in a number of reports and papers (Aitken 1973; Löffler and Margules 1980; Tiver 1981; Ostendorf *et al.* 2009; Taggart *et al.* 2010), there have been no detailed attempts to understand how these factors influence wombat population dynamics at different spatial scales. There had also been no attempts to determine the wombats' fundamental environmental niche in the absence of European anthropogenic influences and hence, how the population might have changed in response to those influences.

These – the, when? where? how many? and why? of the southern hairy-nosed wombat population - are the fundamental questions that we sought to resolve through this research.

**Chapter 2: Historical changes in the distribution of hairy-nosed wombats (*Lasiorhinus spp.*): a review**

Determining the likely distribution of southern hairy-nosed wombats at the time of European settlement would establish their fundamental environmental niche, free of the anthropogenic influences which have transformed the landscape and fragmented the population since that time. This is important for species distribution modelling, as the fragmented landscape currently occupied by southern hairy-nosed wombats is unlikely to capture the full environmental envelope which determines their potential distribution (Araujo and Guisan 2006).

The main findings from this chapter were:

- The distribution of southern hairy-nosed wombats was already fragmented at the time of European settlement, with two distinct groups to the east and west of Spencer Gulf. This splitting of the population was most likely caused by climate change following the last glacial maximum.
- The distribution at the time of European settlement was more extensive that it is today, and it extended much further eastwards and westwards. Some areas in the centre of the distribution from where southern hairy-nosed wombats are currently absent were once densely populated.
- The belief expressed by some landholders that southern hairy-nosed wombats are moving into areas where they have never been seen before is generally not correct. Rather, southern hairy-nosed wombats appear to be recovering areas that they lost as a result of the rabbit plagues of the late nineteenth / early twentieth centuries, and human persecution which destroyed wombats and their warrens to control for rabbits and to open the country for cropland agriculture.

The finding that the population was split as a result of climate change following the last glacial maximum suggests that southern hairy-nosed wombats, like many other wildlife species, may be sensitive to climate change. As a result, we need to understand the likely effects of anthropogenic climate change on the species if we are to make properly informed management decisions on their medium to long-term conservation. If, as appears likely, the distribution is less extensive than would otherwise be the case in the absence of recent anthropogenic factors, then the limits of the current distribution may not represent the true environmental limits. This would need to be considered in any modelling which attempts to determine the impact of anthropogenic climate change on the future population distribution.

**Chapter 3: Using satellite imagery to assess the distribution and abundance of southern hairy-nosed wombats (*Lasiorhinus latifrons*)**

The use of satellite imagery to map the distribution of southern hairy-nosed wombats was first mooted in the late 1970s (Löffler and Margules 1980). However, the capability to do so did not really exist at the time as the resolution of the imagery was too coarse to allow the identification or measurement of warren characteristics. With the ready availability of free, very high-resolution imagery via media such as Google Earth and Bing Maps, as well as easy access to medium and high-resolution imagery from commercial and government organisations like the European Space Agency, the capability to map the wombat distribution from space now exists.

In addition to the indices that we developed to account for potential errors in the interpretation of satellite imagery, we also found a correlation between the size class of warrens (small, medium, large, extra-large) and the number of burrows they contain. This is an important finding, as it allowed us to use the count of the number of warrens in each size class to estimate the number of active burrows in the region, based on the observed ratio of the number of active burrows to total burrows. By multiplying this count by an index of the number of wombats / active warren, we could then estimate the population size; allowing us to both map the distribution and estimate the population abundance from satellite information. As this goes to the heart of what we were trying to achieve from this project, it was an important finding.

Changes in the proportion of active burrows may also provide important clues regarding whether the population is increasing or decreasing. A high proportion of active burrows is likely to indicate a population which is increasing and digging new burrows, whereas a decrease in the proportion of active burrows is likely to be indicative of a population in decline, as the wombats die out and burrows are abandoned. As such, we suggest that this metric is fundamental to our understanding of both the size of the wombat population and the population trend.

An unexpected discovery from this research regarding population trends was that it revealed evidence for different population growth pathways between some of the regions where wombats can be found. The Nullarbor Plain region had a significantly higher proportion of large warrens compared to both Western Australia and the Gawler Ranges, which had a significantly higher proportion of small warrens (all regions had a similar proportion of medium-sized warrens). These regions all appear to be experiencing population growth. However, while in all three regions there appears to be an increase in local area abundance – which results in an increase in the size of many warrens (Reichman and Smith 1990) – in Western Australia and the Gawler Ranges there has also been a marked expansion in geographic distribution, which necessarily results in the construction of new, initially small, warrens.

**Chapter 4: Southern hairy-nosed wombats (*Lasiorhinus latifrons*) in the Gawler Ranges region of South Australia: population growth from 1988 – 2016**

Except for some preliminary surveys, the Gawler Ranges / Lake Harris region became the first population area that we surveyed in detail. Based on the published information we expected to find wombats in relatively low numbers, in two distinct groups to the south and west of Lake Acraman and in the catchment area to the west of Lake Harris. However, what we found was astonishing, and every day brought fresh surprises regarding just how widespread and abundant the wombat population was in the region.

The wombat population in the Gawler Ranges / Lake Harris region was not just more widespread and abundant than what had been reported in the 1980s, it was up to ten times larger. Rather than just being restricted to two population groups, wombats could now be found all over the region, in the area between and for up to 40 km beyond the previously described boundaries. The Lake Harris group, which had been described as 'fragile' with a population density of ~ three wombats / $km^2$ (St.John and Saunders 1989) now had population densities of > 50 wombats / $km^2$ in some locations, including in areas which had previously been described as being wombat free. To the south of Lake Acraman, at locations such as Hiltaba Station where wombats had once been described as 'inconspicuous' (Aitken 1971), population densities of ~ 100 wombats / km$^2$ were now common in some areas. We presented this information at Hiltaba Station in mid-2018, and some people in attendance who remembered the area from the 1970s confirmed this as being a true representation of the changes which had occurred since that time.

This survey highlighted a very important issue for our ongoing research; either the wombat population had grown substantially over the previous 30 years since the 1980s, or the earlier surveys did not reveal the true extent of the population that existed at the time. Notwithstanding which of these alternatives was correct, there was a strong case to be made for an upwards revision in the size of the wombat population. Our initial assessment was that it was a combination of both of these possibilities, but it was not until we undertook surveys of the other regions that this hypothesis was confirmed.

**Chapter 5: Southern hairy-nosed wombats (*Lasiorhinus latifrons*) in Western Australia: out of sight, out of mind**

Prior to this study very little was known about the southern hairy-nosed wombat population in Western Australia. As was the case for the Gawler Ranges, what we found in Western Australia was quite different to our expectations. Rather than being just a few isolated colonies in the far east of the state near the South Australian border, the distribution extended from the border westwards for ~ 350 km to around Caiguna, and northwards from the Eyre Highway for approximately 75 km. This made the distribution comparable in geographic extent to the Nullarbor Plain population on the South Australian side of the border. While the distribution was patchy, the overall population abundance was estimated as ~ 90,000 individuals, which is 80% greater than the population in the Murraylands. Given the attention which has been placed on studying and conserving southern hairy-nosed wombats in the Murraylands, the fact that such a large population group had escaped attention until now is remarkable.

An important implication regarding wombats in Western Australia is what it means for wombat conservation and management. The fact that such a large population was not factored into earlier population estimates means that the some of the assumptions underpinning wombat management are incorrect. As is the case in South Australia, wombats are a protected species in Western Australia. While landholders are able to apply for a permit to cull perceived over-abundances, no permit has ever been issued or applied for in the state (K. Atkins, Department of Parks and Wildlife, email communication, 15 June 2017). This is despite one landholder advising us that wombats now represented the number two threat to grazing in the area (behind kangaroos but ahead of dingoes and wild dogs), and that they could no longer muster livestock on motorbikes due to safety concerns regarding wombat burrows.

We presented these findings at the International Mammal Congress conference in Perth in 2017, and from the reactions it would appear that the relevant authorities in the state were not aware of the situation. Now that the presence of wombats in the state is being recognised, we suggest that a policy and / or approach to their management will need to be formulated. Although wombats are found in remote, sparsely populated areas of Western Australia and are essentially 'out of sight, out of mind', if the population continues to grow (as appears likely), ignoring them will not be a viable strategy for the long-term health of either the wombat population or for agriculture.

**Chapter 6: A search fails to find any evidence for the on-going presence of southern hairy-nosed wombats (*Lasiorhinus latifrons*) in south-western New South Wales**

Throughout the course of this research we have received report of wombats from several locations well outside their expected distribution, such as near Andamooka in the north of South Australia (ABC News 2016) and Ned's Corner in north-western Victoria (ABC News 2011). Investigation of these reports did not reveal extant population groups; rather, they appeared to be cases of deliberate releases of animals into the area. The reports of two small colonies of wombats in the south-west corner of New South Wales were more credible (Adams 1997) and they warranted a closer examination.

While there were anecdotal suggestions that the original reports may have been spurious (W. Duncan, owner of Talgarry Station, pers. comm.), we also noted other anecdotal claims which suggested that they may have been valid (D. Alpers, email communication, 3 October 2018). Unfortunately, at the time of submission of this thesis, the detailed accounts of the original reports and the supporting evidence for the claims could not be located. Notwithstanding this, we could find no evidence of wombats at the locations where they had been reported. Consequently, we concluded that southern hairy-nosed wombats are probably no longer present in the region.

## Chapter 7: A comparison between video and still imagery as a methodology to determine southern hairy-nosed wombat (*Lasiorhinus latifrons*) burrow occupancy rates

Estimating how many wombat there might be at the broad scale has always been problematic. The most widely used proxy, the index of wombats / active burrow, offers a realistic option, but it has a number of problems that need to be resolved to ensure its efficacy. Principle among these is the index itself; exactly how many wombats are there per active burrow? Does it vary spatially and / or temporally? And what is the best way to calculate the index to reduce the potential for error?

The indices that we calculated for the Murraylands and Eyre Peninsula – 0.43 and 0.42 respectively – reiterate figures that were calculated in the past (Tiver 1981; McGregor and Wells 1998), which suggests that they are probably robust enough to use for most broad area population surveys. The issue about potential variations due to local conditions still warrants further study, and we recommend that this research be ongoing. We would not support the use of these indices for small scale studies.

In addition to our findings on the number of wombats per active burrow, the use of video cameras revealed other information which will prove useful for future research. These include the discovery that a burrow that appears to be active may not necessarily be so, as wombats and other species can visit the entrance to the burrow, disturb the soil, and deposit scats without ever entering, which creates the impression that the burrow is in use. Interestingly, this is not a new finding, as the initial research undertaken in the 1980s also included burrows which were assessed as active, but from which no wombats were captured (Tiver 1980; Tiver 1981).

While this study focussed primarily on calculating an updated index of wombats / active burrow, the analysis of the camera performance also provided valuable lessons for future research; and not just for wombat research. These lessons include:

- Cameras facing directly into a burrow may not be triggered by an animal emerging from its burrow and moving towards the camera, and data can be missed as a result. For best results, any burrow cameras should be positioned at an angle to, and at a distance of ~ 3-5 m from the burrow entrance.

- Video provides a great deal more information than still imagery, but it is also data intensive and can quickly fill the data storage capacity of a camera, especially if high-definition video is recorded.
- Wildlife cameras can experience a high 'false-positive' rate, when the camera is triggered without there being any obvious target within the field-of-view. Virtually all of the false positives that we experienced occurred in the afternoon, with almost none occurring at night. This strongly suggests that the camera is being triggered by solar radiation either heating the ground in front of the camera or the camera body itself.

**Chapter 8: The species-wide distribution and abundance of southern hairy-nosed wombats (*Lasiorhinus latifrons*)**

Using the methodology described in the earlier chapters, we completed a species-wide population survey of all the regions where southern hairy-nosed wombats are located. This revealed that the wombat population is now much larger than was reported in the 1980s; with an overall estimate of ~ 1.3 million individuals. Despite this, as was the case for the Gawler Ranges and Western Australia, establishing a true population trend is difficult as we discovered more evidence that suggests that the surveys undertaken in the 1980s were unlikely to have revealed the full extent of the population that existed at the time.

A good example of this is the map purporting to show the wombat distribution on the Nullarbor Plain in the 1970s / 80s (Chapter 8 Figure 8). As well as suggesting that the distribution did not extend any further west than Koonalda homestead (which we believe is unlikely, given the large population in Western Australia), the map also shows a number of isolated colonies extending northwards from the main population group towards the transcontinental railway line. These intrigued us, as they are oriented in straight lines extending roughly north-south rather than being scattered as we would have expected for isolated colonies. The reasons for this became clear when we overlaid the map onto satellite imagery and discovered that the locations of the isolated colonies correlated with the roads which link the Eyre Highway with towns on the railway line. It appears as if the surveys followed these roads and discovered colony groups in the process, but because of the inaccessibility of the areas between the roads they could not survey those areas to check for the presence of wombats. As a consequence, these areas were left blank on the map. By analysing satellite imagery, we can confirm that wombats are now present in these areas, and given that wombats were present in the 1980s in the vicinity of the roads, we suspect that they were probably present in-between as well. This means that the distribution map probably understated the northerly extent of the population at the time.

While it appears likely that there has been species-wide population growth since the 1980s, especially in the Gawler Ranges and Nullarbor Plain, the trend across, and within, the regions has not been uniform. There are local factors such as conservation efforts, over-grazing, weed infestations, and wombat control actions which are driving population increases in some areas and decreases in others. A good example of this is Kooloola and Portee stations in the Murraylands, where surveys suggest the wombat population has declined since the early 1990s, most likely as a result of overgrazing by livestock (Taggart and Robinson 2008). However, at the adjacent Moorunde Wildlife Reserve there has been in a four-fold increase in the wombat population since the removal of livestock in the 1960s (Taylor 2015). This suggests that there is no 'one size fits all' approach to wombat management, and local factors are likely to be just as important as broad-scale considerations when determining the best approach.

## Chapter Nine: Southern hairy-nosed wombats (*Lasiorhinus latifrons*): why are they 'there' but not 'there'?

This chapter represents the culmination of our research, as it used the results from all the previous chapters to build a picture of where wombats can be found and the reasons for their presence or absence from some areas. An understanding of this is important because it will allow us to make better informed decisions regarding wombat conservation and management. It also provides an underpinning for future research on how the population might respond to climate and landscape changes, and it identifies a number of key areas where more information is needed.

The principle environmental factors affecting wombat distribution and abundance are rainfall, rainfall variability, soil texture, and vegetation. The first two are the most important when considering the long-term prospects for broad-scale wombat conservation and management in the context of anthropogenic climate change, as the predicted changes to rainfall and rainfall variability are both likely to have a negative impact on wombats.

Conversely, soil texture is largely a fixed variable that will not change significantly, but as southern hairy-nosed wombats are fossorial animals, soil texture is crucial to determine where they can dig and the stability of their burrows. This factor alone is sufficient to describe the gap between the Nullarbor Plain and Gawler Ranges population groups (dunefields high in sand and low in clay content), and is a factor (with vegetation and terrain) which explains why the pre-European wombat population was not contiguous to the north of Spencer Gulf (dunefields changing to hard clay soils, rocky ranges, and mallee woodlands).

While vegetation is an important variable that affects local area abundance, it is not a major limiting factor which determines its current distribution. That being said, landholders have consistently claimed that the clearing of woodlands for agriculture favours wombats (Stott 1998), and the evidence from our research would support that view. The logical extension of this is that while the distribution of wombats has shrunk and fragmented since European settlement, the population abundance in some areas is likely to have increased as a result of land clearance. While we have no data to confirm this one way or the other, an examination of the pre-European vegetation maps suggests that many of the current zones of conflict between landholders and wombats (e.g. the Far West Coast of South Australia) may have been exacerbated by land clearance, as these areas which are now heavily favoured by wombats were once dominated by mallee woodlands, which would have had a much lower occupation rate than the open grasslands that exist today.

Notwithstanding the effects of these environmental variables on wombat distribution and abundance, the most important factor which shapes the wombat population today is anthropogenic land-use practice. Chapter two of this thesis showed that the distribution of southern hairy-nosed wombats was more extensive at the time of European settlement, and that the introduction of feral species (especially rabbits) and human persecution caused the distribution to contract and the abundance to decline markedly. Indeed, while wombat numbers appear to be recovering in most areas now that rabbits are under effective control, they remain conspicuously absent from areas of cropland agriculture. Nowhere is this more noticeable than on the Yorke Peninsula and Eyre Peninsula / Far West Coast, from where wombats remain almost completely absent except in grazing lands, remnant bushland or protected areas, and where a large proportion of the illegal control activities are conducted to keep wombats from occupying croplands.

Finally, there are a number of areas where we would recommend further research to build upon these results described in this thesis. These include:

- Characterise the relationship between dingoes and wombats.
- Quantify the effects of grazing competition between wombats, livestock, and native and introduced herbivores.
- Map and correlate the effects of topography and colluvial in-filling on the Nullarbor Plains with local area distribution and abundance.
- Determine the likely changes in wombat distribution and abundance as a result of anthropogenic climate change.

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# Annex 1: Publications and Conferences

## List of Publications

**Swinbourne, M.J.**, Taggart, D.A., Sparrow, E., Hatch, M. and Ostendorf, B., 2016. Ground penetrating radar as a non-invasive tool to better understand the population dynamics of a fossorial species: mapping the warrens of southern hairy-nosed wombats (*Lasiorhinus latifrons*). *Wildlife Research*, *42*(8), pp.678-688. (Honours thesis)

**Swinbourne, M.J.**, Taggart, D.A., Peacock, D. and Ostendorf, B., 2017. Historical changes in the distribution of hairy-nosed wombats (*Lasiorhinus* **spp**.): a review. *Australian Mammalogy*, *39*(1), pp.1-16.

**Swinbourne, M.J.**, Taggart, D.A., Swinbourne, A.M., Lewis, M. and Ostendorf, B., 2018. Using satellite imagery to assess the distribution and abundance of southern hairy-nosed wombats (*Lasiorhinus latifrons*). *Remote Sensing of Environment*, *211*, pp.196-203.

**Swinbourne, M.**, Taggart, D., Swinbourne, A., and Ostendorf, B. (2018b). Southern hairy-nosed wombats *(Lasiorhinus latifrons*) in the Gawler Ranges region of South Australia: population growth from 1988 to 2016. *Australian Mammalogy*, in press.

**Swinbourne, M.**, Taggart, D. and Ostendorf, B., 2018. A comparison between video and still imagery as a methodology to determine southern hairy-nosed wombat (*Lasiorhinus latifron*s) burrow occupancy rates. *Animals*, *8*(11), p.186.

**Swinbourne, M.**, Taggart, D. and Ostendorf, B., Southern hairy-nosed wombats (*Lasiorhinus latifrons*) in Western Australia: out of sight, out of mind, *Australian Mammalogy*, accepted pending revision.

**Swinbourne, M.**, Taggart, D. and Ostendorf, B., A search fails to find any evidence for the on-going presence of southern hairy-nosed wombats (*Lasiorhinus latifrons*) in south-western New South Wales, *Australian Mammalogy*, accepted pending revision.

## Conference Presentations

**Swinbourne, M.**, Taggart, D. and Ostendorf, B., (2015), Historical changes in the distribution of hairy-nosed wombats (*Lasiorhinus* **spp**.), Australian Mammal Society, Annual Scientific Meeting, Hobart, July 2015.

**Swinbourne, M.**, Taggart, D. and Ostendorf, B., (2015), Using ground penetrating radar for wildlife research: mapping the warrens of southern hairy-nosed wombats, Society of

Exploration Geophysicists (SEG), International Exposition and 85th General Meeting, New Orleans, October 2015.

**Swinbourne, M.**, Taggart, D. and Ostendorf, B., (2016), Historical changes in the distribution of hairy-nosed wombats (*Lasiorhinus* **spp**.), South Australian Government Natural Resources Management, University of Adelaide, April 2016.

**Swinbourne, M.**, Taggart, D. and Ostendorf, B., (2016), Hairy-nosed wombats: when, where, why, how and what? Natural History Society of South Australia, Annual Meeting, University of Adelaide, May 2016.

**Swinbourne, M.**, Taggart, D. and Ostendorf, B., (2016), Southern hairy-nosed wombats (*Lasiorhinus latifrons*) in the Gawler Ranges region of South Australia: population growth and distribution expansion since 1990, Australian Mammal Society, Annual Scientific Meeting, Alice Springs, September 2016.

**Swinbourne, M.**, Taggart, D., Achurch, H. and Ostendorf, B., (2017), Southern hairy-nosed wombats (*Lasiorhinus latifrons*) in Western Australia: out of sight, out of mind, International Mammal Congress Conference, Perth, September 2017.

**Swinbourne, M.**, Taggart, D., Porter-Dabrowski, G., Swinbourne, A. Turner, D, and Ostendorf, B., (2017), Wombats from space: a multi-method, multi-scale approach to assessing southern hairy-nosed wombat population and abundance, Surveying and Spatial Sciences Institute of South Australia, Annual Conference, August 2017.

**Swinbourne, M.**, Taggart, D. and Ostendorf, B., (2018), Management of southern hairy-nosed wombats (*Lasiorhinus latifrons*), in South Australia: what is the real state of affairs? South Australian Government Natural Resources Management, University of Adelaide, April 2018.

**Swinbourne, M.**, Taggart, D. and Ostendorf, B., (2018), Burrow occupancy and wombat behaviour at Moorunde Wildlife Reserve, Natural History Society of South Australia, Annual Meeting, University of Adelaide, May 2018.

**Swinbourne, M.**, Taggart, D., and Ostendorf, B., (2018), Comparing video and still imagery to assess the burrow occupancy rate of southern hairy-nosed wombats (*Lasiorhinus latifrons*): a cautionary tale in the use of motion-activated cameras, Australian Mammal Society, Annual Scientific Meeting, Brisbane, July 2018.

**Swinbourne, M.**, Taggart, D., and Ostendorf, B., (2018), Using remote sensing and spatial science to assist with the management of southern hairy-nosed wombats, Wombats Through Time and Space Conference, University of Adelaide, September 2018.

**Poster Presentations**

**Swinbourne, M.**, Taggart, D., and Ostendorf, B., (2018), Southern hairy-nosed wombats: why are they 'there', but not 'there'?, Wombats Through Time and Space Conference, University of Adelaide, September 2018.

**Social Media**

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