Life in the big city
– identifying bandicoot presence
in the urban matrix

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A thesis submitted in partial fulfilment of the requirements
for the degree of Master of Research

December 2018

Statement of Originality

This work has not previously been submitted for a degree in any university. This thesis does not contain previously published material, with the exception of the cited references.

______________________________ Date: 31 December 2018

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Note to the examiners

This thesis is written in the format of a journal article from an original paper for the **Journal of Urban Ecology** except for the formatting requirements from the Department of Biological Sciences, Macquarie University.

Cover image: Long-nosed bandicoot *(Perameles nasuta)* sneaking pet food in suburban home in Newport (former Pittwater LGA), Sydney 2106.

Photo: Sonja Elwood, 28 March 2018

Ethics Reference Number: 5201800111

TABLE OF CONTENTS

TABLES, MAPS AND FIGURES

ABBREVIATIONS

ABS Australian Bureau of Statistics

LGA Local Government Area

NSW New South Wales

OEH Office of Environment and Heritage

ACKNOWLEDGEMENTS

I would like to give many thanks to my supervisors Professor Michelle Leishman and Dr. Alexandra Carthey throughout the research of this thesis.

Huge thanks to Dr. Megan Brewer for assistance with editing and whose kindness and encouragement made sure this thesis was completed!

Huge thanks to Cameron Fisher for personalised IT support at home and giving up two whole days over the Christmas-New Year period when my computer died (twice) - life saving!

Huge thanks to Rebecca for coming around NY's eve at 8pm when my computer crashed for the third time just before submission and helping me limp over the line with a laptop!

Special thanks and shout out to Will Farebrother for his outstanding GIS skills preparing the geo-spatial analysis and mapping required for this project and for being an all-round great guy!

Special thanks to Dr. Drew Allen for amazing assistance, advice and time spent with the R coding and statistical analysis necessary for this research and to Dr Andie Pryce for help with editing and statistical interpretation!

Many thanks to Fiona Jones (MQU Library) for support and training in the use of EndNote and helping fix my reference library every time I managed to break it and for making me smile!

Many thanks to Northern Beaches Council for being so flexible and allowing me time to do this.

My thanks to all the local government biodiversity officers who took the time to assist me in data collection in their respective areas and sharing their local knowledge with me.

My thanks to Cumberland Ecology for allowing me to attend 2018 bandicoot surveys of North Hd.

Special thanks, as always, to the Sydney Wildlife volunteer members and dear friends who have amazed, inspired and humbled me every day for 21 years but especially this year in my studies!

My thanks to the NSW Office of Environment and Heritage Officers, Ian Geers and Alison Foster, for assistance with Bionet and Wildlife Licensing Managers, Peter Stathis and Ron Haering, for their encouragement and commitment to wildlife and the rehabilitation sector in NSW.

My thanks to Milad Yousif (MQU Science IT) for IT support at uni.

And last but not least, special thanks to my son Callum, best mate Lachie, mum, dad, sister Trudes and bro-in-law Si, sister Kylie and my kiwi crew at home in NZ for being such legends and my cheering squad! And also to Kai, Anna, Sandra, Lynleigh, Nicole, Aaron and Damian for your kindness and support getting me through this year and the rest of my aussie crew for the constant encouragement - there's a little bit of all you in this!

And to my beautiful Gran who I miss every day – this is for you!

ABSTRACT

The greater Sydney region provides habitat for two species of Peramelidae, the southern brown *(Isoodon obesulus obesulus)* and long-nosed bandicoot *(Perameles nasuta).* Both species have suffered significant range contraction since colonisation, yet little is known of their ecology and behavior. The endangered southern brown bandicoot is found only in Sydney's northern national parks and is rarely sighted. The long-nosed bandicoot is listed as endangered in Sydney's inner west and Manly's North Head yet is a common exploiter of lawns and parks in other suburbs adjoining national parks.

This study used GIS mapping and statistical analyses to examine five urban land use and four demographic variables likely influencing bandicoot presence in the Sydney urban matrix. Datasets include previously unused wildlife rescue and Council records mapped in five-year time slices over the past twenty-five years. The quality of datasets proved insufficient to establish significant relationships with all but one land-use variable, agricultural and rural lands, which showed a strongly negative association with bandicoot observations.

This study demonstrates greater quality, larger scale datasets and the principles of ecologically sustainable development are necessary to make informed policy and planning decisions if long-nosed bandicoots are to be sustained within the intensifying Sydney urban landscape.

Keywords: bandicoot, *Isoodon obesulus, Perameles nasuta,* Peramelidae, urban adapter, urban ecology, urbanisation, Sydney.

INTRODUCTION

Bandicoots are small, solitary, ground-dwelling, nocturnal, omnivorous marsupials that, together with bilbies, are part of the Peramelid family (Thomas, 1888, Ashby et al., 1990, Dowle, 2012, Travouillon and Phillips, 2018). Possessing polyprotodont teeth similar to carnivorous dasyurids, syndactylous toes found in marsupial herbivores (Jones, 1923, Tate, 1947) and a placental structure and persistent corpus luteum more in common with eutherians (Hill, 1895, Close, 1977), their evolution and taxonomy remains unresolved today with few fossil records available to provide further clues. At the time of European colonisation in 1788, it is likely the Australian Peramelid family comprised more than 20 species with at least one species represented in almost every Australian landscape (Ashby et al., 1990).

Today, however, only six species of this family remain across Australia with only two still regarded as relatively common in the wild: the long-nosed bandicoot *(Perameles nasuta)* and the northern brown bandicoot *(Perameles macrourus)*. The remaining four species are listed as either critically endangered, endangered or extinct in the wild (Department of Environment and Energy, 2018). In Australia's largest and densest city, Sydney (Australian Bureau of Statistics, 2017), two bandicoot species persist: the long-nosed bandicoot and the endangered southern brown bandicoot *(Isoodon obesulus obesulus)* (Department of Environment and Energy, 2009). As the urbanisation of Sydney is currently intensifying, this thesis investigates variables related to long-nosed and southern brown bandicoot presence and persistence in this growing metropolis.

Urbanisation and Ecologically Sustainable Development (ESD)

Sydney is Australia's largest city, accommodating 5.1 million people over an estimated area of approximately 12,368 km^2 (Australian Bureau of Statistics, 2017). It is also the densest city in terms of population, at an average of approximately 398 people per km^2. The built urban area is estimated at 4,064 km^2 which translates to a mean density of 1,237 persons per km^2 but ranging between 1,000 persons per km^2 to 17,500 per km^2 (Australian Bureau of Statistics, 2015).

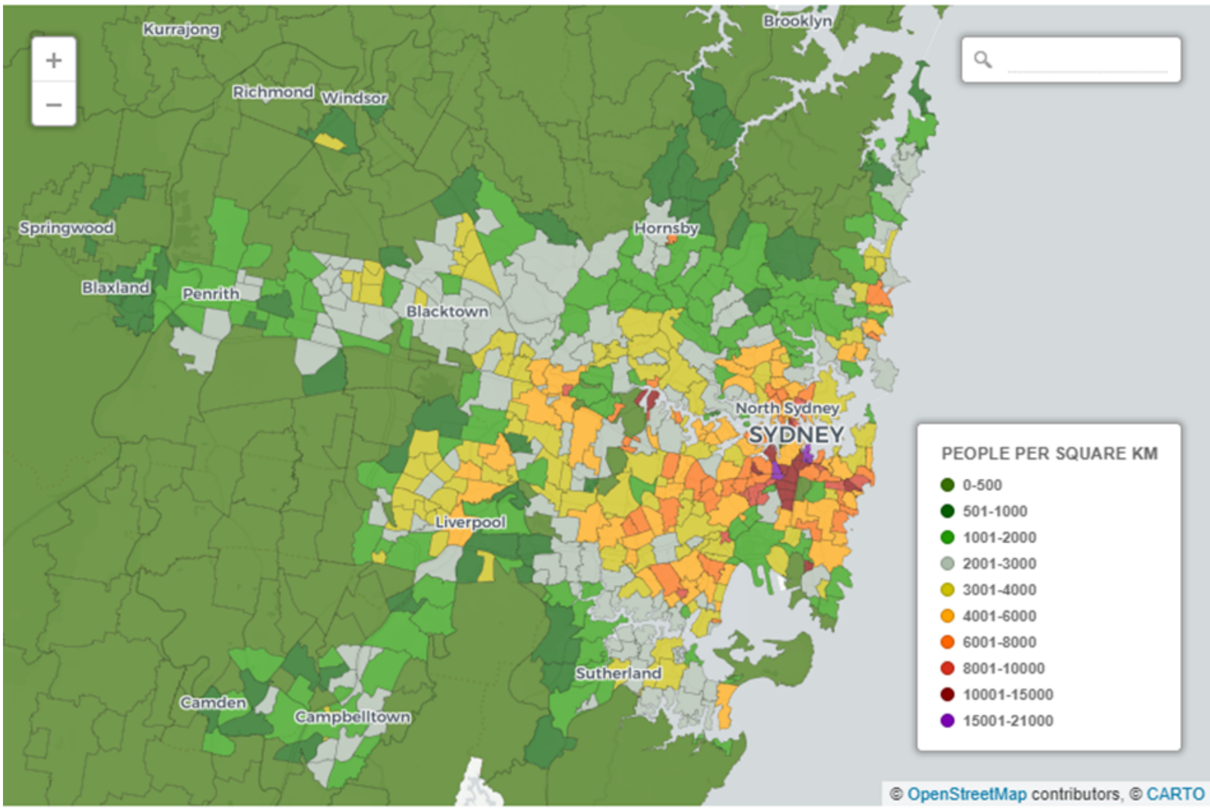


Figure 1 – Population Density per km^2 in the greater Sydney metropolitan area.
Map by ©OpenStreetMap contributors (https://www.openstreetmap.org/copyright) and ©CARTO (https://carto.com/attribution/). Licensed under https://creativecommons.org/licenses/by-sa/2.0/
https://www.smh.com.au/business/the-economy/the-truth-about-how-many-people-are-being-packed-into-sydney-20180621-p4zmww.html
Nigel Gladstone – Sydney Morning Herald - 22 July 2018

Despite this, relatively large areas of native vegetation remain intact in national parks across the greater Sydney Basin, although significant losses have occurred in Sydney's western plains grasslands, woodlands and forest since European occupation. The Sydney Basin is regarded as a national biodiversity hotspot, providing habitat for 2 endangered and 4 vulnerable frog species, 54 vulnerable and 14 endangered bird species, 25 vulnerable and 3 endangered mammal species and 11 vulnerable and 2 endangered reptile species (New South Wales Office of Environment and Heritage, 2016c).

Urbanisation is a current global trend (Hillman et al., 2017, Aronson et al., 2014, Soga et al., 2014, Sol et al., 2013). In existing cities, such as Sydney, it coincides with increased development density and expanded urban sprawl to accommodate an increasing population.

Urbanisation presents a number of challenges for many species of native fauna (Driscoll et al., 2018, Villaseñor et al., 2017, Aronson et al., 2014, Sol et al., 2013, Garden et al., 2010). Some have become extinct, whilst others are limited to bushland remnants or national parks (Ramalho et al., 2018, Hillman et al., 2017, Recher, H., 2009). Conversely, a small number of species may benefit to varying degrees within these novel urban environments (Maclagan et al., 2018, Shea, 2010, Wilks, 2009, Recher, 2009), as particular niche resources are modified, increasing access to food (Hillman et al., 2017) and reducing competition with other species. These species are known as urban-adapters (Villaseñor et al., 2017, Bryant et al., 2017, Lowry et al., 2013, Fitzgibbon et al., 2011, Leary et al 2010).

The problems caused by urbanisation in Australia for native species are already well recognised. In 2004 the New South Wales Zoological Society released a publication entitled 'Urban Wildlife: More Than Meets the Eye', comprising a number of papers exploring (what was then) the emerging discipline of urban wildlife research, and the need to develop specific plans for its conservation management (Lunney and Burgin, 2004, Catterall, 2004, Davies et al, 2004, Grayson and Calver 2004, van De Ree 2004, Buckley, 2004, and Burgin, 2004). This was followed in 2012 by a second publication 'The Natural History of Sydney' that draws together historical survey records and depictions of several regions of Sydney's natural environment and fauna and explores the ramifications of its ongoing expansion (Lunney et al., 2012, Brown and Bernhard, 2010, Harris et al., 2010, White, 2010, Shea, 2010, Recher, 2009).

In the face of a predicted population increase of approximately three million people in Sydney by 2056 along with commensurate housing and infrastructure (Greater Sydney Commission, 2018), it will remain challenging to ensure Sydney's bandicoots and biodiversity remain viable in this changing landscape. This will require careful consideration and incorporation of the principles of ecologically sustainable development (ESD) and the 'precautionary principle' into policy and development plans.

The terms ecologically sustainable development (ESD) and the 'precautionary principle' are defined in Australia's National Strategy for Ecologically Sustainable Development 1992 and the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act), and require state and local government organisations to report their initiatives and impacts on the natural environment and how they have been mitigated (Department of Environment and Energy, 1992). These principles are relevant to planning and policy makers today in the face of ongoing population growth and development expansion in Sydney, if we want to ensure biodiversity is protected and maintained into the future.

Bandicoots in the greater metropolitan Sydney region

Both the southern brown bandicoot and the long-nosed bandicoot have persisted in the current urbanised city of Sydney but to differing degrees. The southern brown bandicoot is known as a shy, cryptic and largely heath-dwelling species (Van Dyck and Strahan, 2008, Atkins, 1999, Atkins, 1998, Paull, 1995, Hocking, 1990, Gordon and Hulbert, 1989) with last known sightings restricted to Sydney's national parks (New South Wales Office of Environment and Heritage, 2018). This species is listed as endangered under the NSW Biodiversity and Conservation Act 2017 (formerly under the NSW Threatened Species Conservation Act 1995 and nationally under the EPBC Act 1999, as well as under state legislation in Victoria, South Australia, Queensland, and Tasmania. Throughout NSW and their national range, southern brown bandicoot populations are isolated from one another (Department of Environment and Energy, 2009).

The long-nosed bandicoot, by comparison, occurs in a wide range of habitats throughout coastal Queensland, New South Wales, and Victoria. In Sydney, they were formerly quite widespread (Marlow, 1958) but appear to have declined in many areas (Coates et al., 2008, Scott et al., 1999. Long-nosed bandicoots are now only relatively free-living and abundant in parts of former Warringah and Pittwater local government areas (LGAs)(Elwood, pers. obs., 2018).

Two endangered long-nosed bandicoot populations also occur in Sydney. One is at North Head National Park in the former Manly LGA, where despite its isolation the population appears to have somewhat recovered since its listing in 1997 (NSW Scientific Committee, 1997) (NSW Scientific Committee, 1997, Cumberland Ecology, 2018). The second centres around Dulwich Hill in Sydney's inner west, where numbers have dwindled further since its listing in 2008 (NSW Scientific Committee, 2008). This population came to light in scientific circles in the early 2000s and was noted to be very small, which suggests that it has not been a thriving population for some time. Despite formal surveys, no bandicoots have been sighted in the inner west since 2016 (Price, 2016).

As Sydney continues to grow, persistence of these urban bandicoot populations becomes increasingly difficult. The long-nosed bandicoot is likely declining in numbers in some areas and suffering fragmentation and isolation (Cumberland Ecology, 2018, New South Wales Office of Environment and Heritage, 2016a, Price, 2016).

Pressures on bandicoot persistence

There are several pressures on bandicoot persistence including habitat loss, fragmentation and isolation of populations particularly in urban settings where bushland remnants succumb to development or existing land blocks are sub-divided to accommodate more people (Ramalho et al., 2018). This makes dispersal difficult and places bandicoots at risk of predation by feral and domestic animals, another significant threat to all small ground mammals (Dickman, 1994). Dispersal through the urban matrix also makes bandicoots vulnerable to motor vehicle strike whilst attempting to navigate roadways (Scott et al., 1999). Altered or frequent fire regimes, whether as a result of prescribed hazard reduction programs or wildfire, are another impact on bandicoot persistence. This is because fire changes the vegetation structure necessary for bandicoot shelter, predator avoidance and feeding (Dowle, 2012, Braithwaite and Gullan, 1978, Stoddart and Braithwaite, 1979).

Introduced diseases such as toxoplasmosis carried by cats and parasites are another known pressure (Bennett, 2008, Dowle et al., 2013, Hillman et al., 2017). Finally, climate change and drought reduce water availability and soil moisture (Sharma et al., 2018), and are likely to affect invertebrate and fungal abundance, the primary natural food sources for bandicoots (Maclagan et al., 2018, Hughes and Banks, 2011).

Predation by exotic species such as foxes *(Vulpes vulpes)*, cats *(Felis catus)* and dogs *(Canis lupus familiaris)* is another factor affecting bandicoot persistence (Short, 2016, Winnard et al, 2013, Coates and Wright, 2003). Australian fauna between the weights of 35g and 5500g are categorised as ‘critical weight range’ species meaning they are particularly susceptible to predation (Johnson and Isaac, 2009, Recher, 2009). Bandicoots weigh approximately 1500g at adult weight and as ground-dwellers may be particularly vulnerable to these predators. Whilst predation rates by foxes, cats and dogs are largely undocumented in the urban matrix, Australia has one of the highest rates of domestic pet ownership in the world (Animal Medicine Australia, 2016). To our knowledge, there has been no systematic examination of pet ownership rates and how they might relate to bandicoot persistence, movement or dispersal in urban areas.

Ecology and behaviour of bandicoots

In order to counteract the pressures of urbanisation on bandicoot persistence and develop effective conservation strategies for their sustainable management both in the wild and in the urban landscape, we need to understand the habitat requirements and population dynamics of these species (Ashby et al., 1990, Dowle, 2012).

Bandicoots are nocturnal and sleep during the day on the ground in shallow hollowed-out nests in thick vegetation cover (Atkins, 1998, Dowle, 2012). Urban bandicoots are also known to sleep under buildings and infrastructure in a pseudo-burrow type arrangement (Leary et al., 2010). During breeding, emerging pouch young are left in the relative safety of the nest, whilst their mother ventures out to forage (Chambers and Dickman, 2002, Gordon and Hulbert, 1989). Bandicoots are omnivorous, with insects comprising the majority of their diet (Thums et al., 2005, Scott et al., 1999, Mallick S.A., 1997, Quin, 1988, Heinsohn, 1966). Peramelids are also hindgut fermenters possessing a caecum, suggesting that plant material is also a significant part of the diet (Keiper and Johnson, 2004, Gordon and Hulbert, 1989). These requirements for food and shelter suggest that proximity to vegetation is vital to bandicoot persistence (Ramalho et al., 2018, Stirnemann et al., 2015, Hughes and Banks, 2011, Chambers and Dickman, 2002, Bennett, 1990). However, development density is related to the proportion of artificial surfaces and structures within an area and is generally associated with the loss of vegetation (Villaseñor et al., 2017, Schochat, 2006, Caterall, 2004) and is also likely to limit bandicoot persistence. Ideally, effective ecological sustainable development strategies would facilitate the preservation, enhancement or creation of habitat corridors to mitigate these impacts.

Most scientific research on Peramelids has focussed on taxonomy, with little recent ecological work undertaken until the last few decades (Ashby et al., 1990, Atkins, 1998, Dowle, 2012). Consequently, surprisingly little is known about their ecology and behaviour. With regard to their taxonomy, a recent study concluded that the western barred bandicoot (*Perameles bougainville)* is the last remaining extant species of five distinct sub-species in Western Australia and has likely been mistakenly introduced into South Australia as part of a re-introduction program (Travouillon and Phillips, 2018). Such findings reveal that we still understand relatively little about the most fundamental aspects of bandicoot taxonomy, behaviour, and ecology.

Variables to be assessed

In this study I aimed to explore potential relationships between recorded sightings of bandicoots in the greater Sydney metropolitan area and several urban demographic and land use variables.

Given that population increases with urbanisation, population density is considered an important variable. Increasing the proportion of people living in cities also means increased housing, roads and the number of motor vehicles as growing numbers of people require accommodation and transport. Motor vehicle strike is a very real threat for many species of wildlife navigating through the urban landscape (Taylor and Goldingay, 2014, Fitzgibbon et al., 2011, Ben-Ami and Ramp, 2005) as is predation by exotic species such as cats, dogs and foxes (Short, 2016, Winnard et al, 2013, Coates and Wright, 2003). Housing density, car ownership rates and road density levels, pet ownership and fox statistics were therefore also examined to assess their potential impacts on movement by individuals and between populations.

Finally, land use types and vegetative cover vary dramatically within greater Sydney. Some areas retain reasonable amounts of canopy, parks, remnant bushland or proximity to national parks whilst others possess little to none. Comparison of bandicoot presence among differing land use types may help predict the presence of bandicoots in other urban areas.

Project aims

The aims of this study were to:

(i) Determine data availability and quality and the feasibility of a desk-top analysis for predicting bandicoot presence in the urban matrix;

(ii) Determine the effect of demographic or environmental variables including population, housing, and road densities, levels of domestic pet and car ownership and land use on bandicoot persistence in the urban matrix of the greater Sydney metropolitan area.

METHODS

Data Collection and Sources

Fauna Records

I compiled a dataset of long nosed and southern brown bandicoot sightings in the greater Sydney region by making enquiries into all known and potential data sources (summarised in Appendix 1). Both the national and state fauna recording databases were queried. The national fauna recording database, called the Atlas of Living Australia (ALA), is managed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) (CSIRO, 2018) and the state fauna database, Bionet, is managed by the New South Wales (NSW) Office of Environment and Heritage (OEH) (NSW Office of Environment and Heritage, 2018a). A query of the ALA was undertaken on 14th September 2018 and of Bionet on 04th October 2018.

The mapping tools in both packages were used to define the greater Sydney metropolitan area and all Peramelid records within that range were then exported for cleaning. A summary and explanation of data sources for the ALA and Bionet may be found in Appendix 1. In communications with both CSIRO and OEH staff it was confirmed that no displacement of data from any source had occurred and that record locations were as accurate as reported by the data provider as assessed under the data accuracy field included within each dataset. As the NSW state department OEH upload their Bionet records into the national ALA database approximately every two months, all Bionet records were removed from the ALA dataset to avoid duplications and to ensure that the most recently available records were captured from Bionet.

As the records contained within both the ALA and Bionet datasets cannot represent all occurrences of any species over either space or time (New South Wales Office of Environment and Heritage, 2018) the inconsistency of survey effort and related issues around presence or absence must be taken into consideration during analysis.

A significant number of records were removed from both datasets that were identified as 'in-series'. I define 'in-series' as repeated survey records gathered using either cage traps or motion-triggered cameras left *in-situ* for any given survey period. Their removal was based on the assumption that they represent the same animal at a particular location during any given survey timeframe due to cameras taking a “burst” of photos at a time, or in the case of cage trapping, recaptures of the same animal in subsequent visits to the trap.

A further potential source of sighting records resides within local government authorities. In order to gather most recent sightings information from each LGA and to verify whether any or all sightings may already be recorded in either the ALA or Bionet, bushland and biodiversity officers were contacted from each Council in April 2018.

In addition to direct sightings, some Councils operate “cleansing crews” who remove deceased animals from roads and public areas. Council officers were also queried as to whether these records might be available through their customer service request recording systems.

Wildlife rescue organisations represent another potential source of records. There are currently two voluntary native wildlife rescue organisations operating in the greater Sydney metropolitan area, namely Sydney Metropolitan Wildlife Services Inc. (Sydney Wildlife) and the New South Wales Wildlife Information and Rescue and Service Inc. (WIRES). Sydney Wildlife has been operating since 1997 and WIRES since 1985. Although no longer in operation today, a third volunteer wildlife organisation, Australian Wildlife Assistance Rescue and Education Inc. (AWARE) also operated in southern Sydney between 1990 and 2000.

These organisations are licensed by the NSW Office of Environment and Heritage (OEH) to rescue, rehabilitate and release injured, orphaned or diseased native fauna across the greater Sydney metropolitan area. They operate by receiving phone calls from members of the public seeking assistance for a native animal and dispatch trained and authorised volunteer rescuers. Sydney Wildlife, WIRES and the OEH were queried as to any data they may be able to provide relating to bandicoots.

Finally, Taronga Zoo, the Royal Society for the Prevention of Cruelty for Animals (RSPCA) and the Australian Museum were also contacted for bandicoot records as were a small number of researchers and scientists known to be involved in bandicoot research or survey programs.

Data cleaning

Once gathered all records were scrutinised as part of the cleaning process. Records containing bandicoot species other than the long-nosed or southern brown, or only identified to family level were removed as were any records where location was unclear or distance to sighting accuracy was greater than 50 m or unknown. Records in each dataset were examined individually via their unique identification number, date, addresses or GPS points, and comments, and duplicates removed.

Wildlife groups issue all rescued animals with an individual record number and in the case of breeding females, all young are given a record number and also referenced to one another. Records related to one another in this manner were treated as duplications and reduced to a single record to ensure presence-only data were captured for the purpose of statistical analyses.

In all datasets, individual record numbers or identifiers and comments were retained so sightings could be identified from raw data if required at a later date. Council and Sydney Wildlife datasets were stripped of all personal information relating to members of the public and volunteers. Sighting locations in the form of street addresses were geocoded into latitude and longitudes using the online automated software package 'BatchGeo' in preparation for mapping in a geographical information system (BatchGeo, 2018). Once this was complete, street addresses were also removed from these datasets.

Records from all sources, once cleaned, were combined into a master dataset for mapping in a Geographical Information System (GIS).

Data related to the Urban Environment

Population and housing demographic data were obtained via an online enquiry of census data from the Australian Bureau of Statistics (ABS) and categorised by LGA. Several Sydney Councils were amalgamated in May 2016 reducing the number of urban Sydney Councils from 39 to 29. As census data prior to 2016 is aligned with pre-2016 amalgamation Council areas and borders, mapping and statistical analysis was undertaken using these pre-2016 amalgamation LGA scales.

Motor vehicle ownership data for Sydney were sourced from the NSW Roads and Maritime Services through the NSW Government website 'data.NSW', an initiative of the NSW Department of Finance, Services and Innovation as part of the NSW Information and Communication Technology (ICT) Strategy. The dataset provides only a snapshot of car ownership in Sydney over five years from 2010 to 2014 inclusively.

Road density data were drawn from the online NSW Government Spatial Data Catalogue. This dataset was also created by the NSW Department of Finance, Services and Innovation and compiled from a number of government authorities and digitised for the first time in 2005. This dataset is updated daily and is up-to-date to within ten working days of a road plan being registered.

An investigation of ABS census data for domestic dog and cat ownership numbers revealed no available digital or exportable datasets, meaning this variable was unable to be investigated as part of this study. Similarly, data relating to fox sightings held in the state recording system FeralScan – FoxScan (New South Wales Department of Primary Industries, 2009 were also examined and due to the limited amount of data available and timeframe of this study, investigation into these data were also excluded from this study.

All four digitised datasets were transformed to density per km^2 by dividing total numbers by the number of km^2 in each LGA. Datasets are summarised in Appendix 2.

Mapping and Geospatial Data Extraction

The geospatial analyses undertaken within this report were performed using the geographical information system ArcGIS Version 6.2 (Build 9200); Esri ArcGIS 10.5.1.7333 (Environmental Systems Research Institute (ESRI), 2012).

The ArcGIS datasets, layers and shape files of land use categories of the greater Sydney metropolitan area were sourced from the Office of Environment and Heritage Sharing and Enabling Environmental Data (SEED) portal entitled the Australian Land Use and Management (ALUM) Classification Version 8 (2016) Sydney Map sheet 2012 (see Appendix 3). This dataset contained aerial imagery acquired between 2003 and 2013 which formed the base map for further GIS analysis.

The ALUM land use classification system contains six broad land use categories (with a number of sub-categories within each). For the purpose of this study, a small number of categories were revised into five land use categories. Categories (1) and (2) in the ALUM classification were combined into (i) National Parks (including remnant bushland) in this study. Categories (3) and (4) in the ALUM classification were combined into (ii) Agricultural and Rural lands for this project. Category (5) in the ALUM classification was re-classified as (iii) Industrial and Commercial in this study and the sub-categories described within this as Residential and Farm Infrastructure re-categorised in this study as (iv) Urban Residential. The sub-categories described as Rural Residential with Agriculture in the ALUM classification were included in Category (ii) of this study

Agricultural and Rural. Finally, Category (6) in the ALUM classification, Water, was classified as (v) Water in this analysis (see Appendix 4).

Data related to the proportion of land use and bandicoot sightings were then correlated with the 39 Sydney metropolitan pre-2016 LGA boundaries using the Australian Bureau of Statistics, Australian Statistical Geographic Standard 2012-2015 Edition Boundaries (Australian Bureau of Statistics, 2015). LGA boundary extent was selected over alternative classifications (e.g. suburb) as they aligned with demographic digital datasets provided by the ABS also used in this study.

A 1 km^2 grid was then applied using the ArcMap tool 'Fishnet'. A grid-based analysis was selected as it was considered a useful method to achieve finer scale and more meaningful information analysis than LGA-wide analyses would allow. It also enables time series analysis and comparisons between grid cells. A 1 km^2 area grid cell was selected as this correlates well with both demographic census data and as a coarse approximation of bandicoot home range (Ramalho et al., 2018, Wilson, 2004, Paull, 1995, Copley et al., 1990, Lobert, 1990).

Bandicoot sightings were then grouped into five-year time slices over the past 25 years for the periods 01 September 1993 - 31 August 1998, 01 September 1998 – 31 August 2003, 01 September 2003 – 31 August 2008, 01 September 2008 -31 August 013, 01 September 2013 - 31 August 2018. These years and timeframes were chosen as they coincide with (i) a marked increase in bandicoot records likely as a result of the introduction of the New South Wales Threatened Species Act in 1995 (ii) the introduction of desk-top computerised data recording systems and software and (iii) a period of intensifying development and urbanisation within metropolitan Sydney.

As the focus of this study was bandicoot persistence in the urban landscape, bandicoot sightings within national parks were excluded from analysis. Individual sightings within grid cells were merged through a process of 'spatial selection by location', such that each grid cell became a representation of either bandicoot presence or absence per km^2 within an LGA.

All demographic and land use data based at LGA scales were transformed into 1 km^2 density data and proportions of land use per LGA calculated.

The number of bandicoot-occupied 1 km^2 grid cells per LGA and proportions of each LGA occupied by the five land use categories, urban-residential, industrial-commercial, national park, agricultural-rural, and water were then exported from ArcMap polygon shape files into comma-separated value (.csv) Microsoft Excel files in preparation for statistical analysis.

Statistical Analysis

All files were then imported into the statistical software packages 'R' (R version 3.5.1 and R Studio (Version 1.1.456) and merged into one data table for analysis (R Core Team, 2013).

Prior to logistic regression analysis, the five land use categories and four demographic predictor variables were plotted to ascertain levels of collinearity between variables.

Assumptions of normality of the random spatial and temporal variables, LGA size and LGA over time, were tested using quantile-quantile plots (R function 'qqnorm') to ascertain potential effects of inconsistent survey effort and presence–absence uncertainty over both space and time.

A Simpsons Index was calculated for the five land use categories to ascertain if levels of heterogeneity between land use variables in each of the 39 LGAs were sufficient for meaningful analysis.

Subsequently, to investigate the relationship between predictor variables on bandicoot presence and to account for pseudo-absence and inconsistent survey effort over time, a generalised linear mixed effects regression models (family Poisson (loglink)) was generated using the R package 'lme4' for each predictor variable incorporating the function 'offset(log)' of the random variable LGA area to account for differing LGA sizes and subsequent expected bandicoot occurrence over time (Bates et al., 2014, Warton and Aarts, 2013, Warton and Shepherd, 2010). Two models were produced for each variable. The first model used untransformed data whilst the second used a quadratic function (data squared) to assess the linearity of relationships between predictor variables and bandicoot presence and absence over each time slice. An analysis of variance (ANOVA) test was then performed to compare the means of the intercepts of the two models for each land use type.

Ethics Approval

For use of data that contains personal information relating to observers and volunteers, human ethics approval was gained prior to commencement from the Macquarie University Human Ethics Committee (Approval Reference Number: 52012800111).

RESULTS

Data availability and quality

Bandicoot sightings

A total of 2,866 unique records for sightings of long-nosed or southern brown bandicoots in the greater Sydney metropolitan area were acquired for this study. Appendix 1 summarises the data sources, dates and numbers of records removed as part of the cleaning process. The majority of records were obtained from Bionet. These consisted of 1,888 long nosed bandicoot records for the period 22/07/1967 – 23/04/2018, and 218 southern brown bandicoot records over the period 07 September 1967 - 28 April 17. A total of 142 ALA records were available for analysis, consisting of 134 long-nosed bandicoots over the period 12 December 1912 – 14 September 2018 and 8 southern brown bandicoots over the period 31 March 1975 – 28 July 2008.

The survey of local government biodiversity officers contributed a further 38 sightings from five Councils not recorded in Bionet (Appendix 1). Of note was the discovery that less than half of all Councils surveyed contribute to Bionet or the ALA to record local fauna or threatened species.

The request for Council customer service clean-up crew records of roadkill provided a further 105 long-nosed bandicoot records from former Manly, Warringah and Pittwater Councils.

In terms of wildlife rescue data, WIRES was unable to provide records during the time this research was undertaken and OEH confirmed that records from AWARE, having been recorded prior to the year 2000, were not computerised and being paper-based had been lost. Sydney Wildlife however, contributed 785 records for the period 08 July 2003 to 29 September 2017 that were reduced to 524 after the removal of duplications and unverifiable addresses. A further four records were provided for the 2018 period including a rescued long-nosed bandicoot from the endangered inner west population. All wildlife rescue records were of the long-nosed bandicoot.

Taronga Zoo and the Australian Museum confirmed all wildlife data were already recorded in the ALA and the RSPCA found no historical records of bandicoots coming into their organisation.

A small number of Sydney-based bandicoot researchers and ecological consultants were contacted to establish if any further records may be available. This query discovered five further long-nosed bandicoot records not yet uploaded into Bionet between 2016 and 2018.

The complete unique dataset represented data from as early as 1912. As this project focuses only on the last 25 years, the final number of records for long nosed and southern brown bandicoot sightings used in further analyses were 2,694 and 226 respectively.

Geospatial Data

Census information in the form of digital data were available for the years 2006, 2011 and 2016. Data collected in 2016 however were found not to be compatible with previous years as it occurred after Council amalgamations in May 2016 and thus applies to the newly-formed LGAs and was therefore not usable in this study. Due to the lack of digital data prior to 2006, population and housing data gathered from the 2006 census were applied to the time slices 1993-1998, 1998-2003, 2003-2008 and population and housing data obtained from the 2011 census applied to the time slices 2008-2013 and 2013-2018.

Digital car ownership census information was also limited and, unlike other census information, only reported for the years 2010 -2014 respectively. Therefore, a mean was taken of the five years and applied to all time slices. Road density data is updated very regularly and is only reflective of current road densities, - historical datasets are not available. This meant the current 2018 dataset was applied to all time slices.

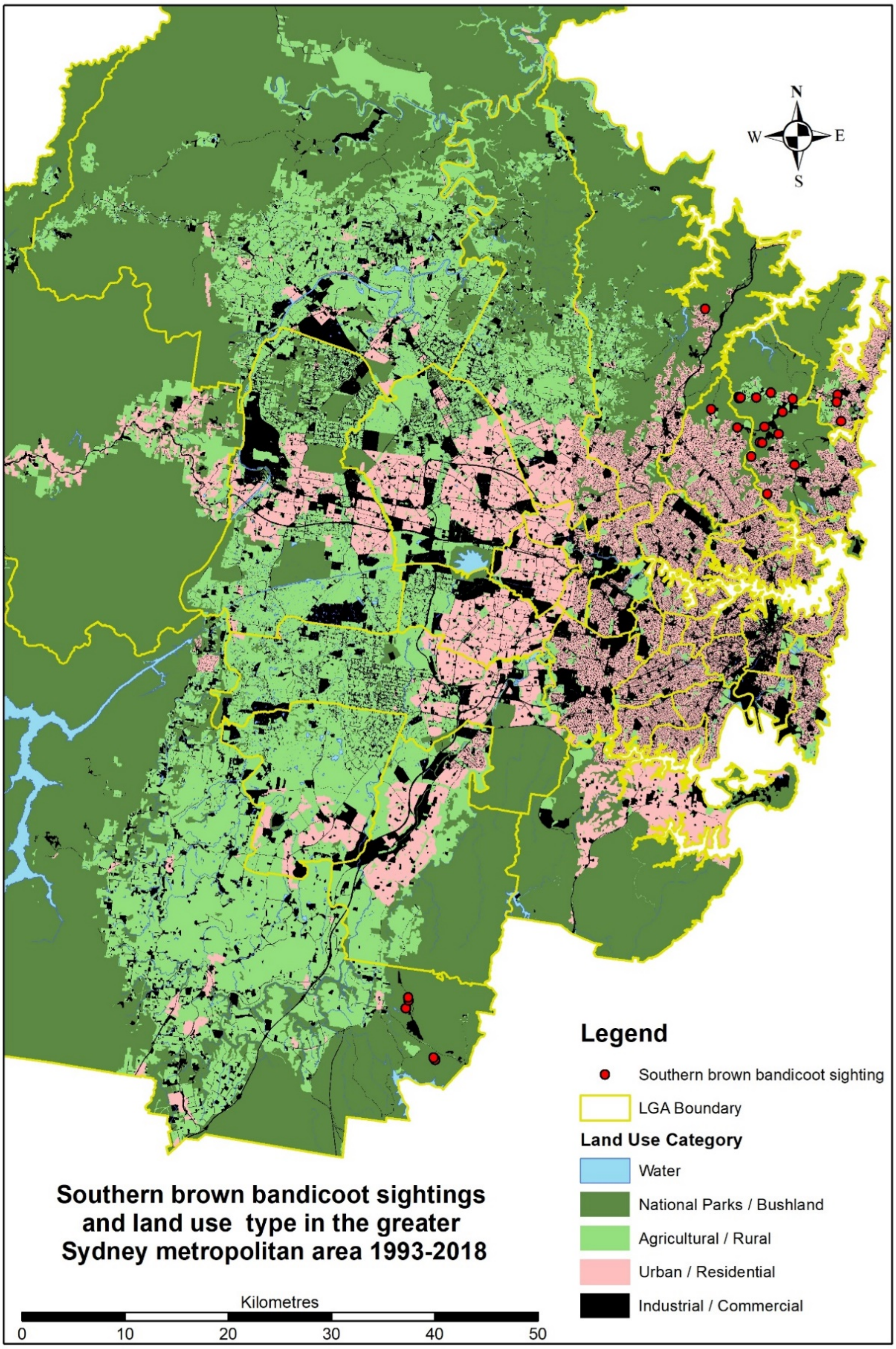
Land use modelling data and shape files obtained from the NSW OEH SEED portal who constructed this dataset using digital aerial imagery gathered over the period 2003-2012 (NSW Office of Environment and Heritage, 2017, Warton and Aarts, 2013). This model provides a snapshot only of the Sydney basin and does not reflect changes in land use over time.

Mapping

Southern brown bandicoot

As this study is specifically interested in bandicoot occupancy within the urban matrix only, once the bandicoot sightings were reduced to presence-only within 1 km^2 grid cells, all grid cells within national parks were removed. The southern brown bandicoot was thus revealed to be extremely data deficient with occupancy in only 22 of the 1km^2 urban grid cells across five LGAs (Hornsby, Ku ring gai, Pittwater, Warringah, and Wollondilly) over the entire 25-year time period (Appendix 5). Statistical analysis was therefore not possible for this species.

Although statistical analysis was not possible, to gain a general idea of the presence of southern brown bandicoots in the urban matrix, the unique sightings were mapped on to the greater Sydney metropolitan area (Map 1). It should be noted when viewing the mapping that southern brown bandicoot sightings within national parks were removed in the geospatial analysis process. The appearance of sightings within these areas in Map 1 is due to their detection under a different land classification within or in close proximity to a national park. For example, on a road (classified as industrial and commercial) or within small townships in a national park (classified as urban residential) or in some form of rural, open or agricultural green space within or adjoining a national park (classified as agricultural and rural).



Map 1 – Southern brown bandicoot sightings outside national parks in urban Sydney by land use category and LGA 01 September 1993-31 August 2018

Note the red dots represent sightings only and not occupancy in 1km^2 grid cells.

Long-nosed bandicoot

Long-nosed bandicoot presence was detected in a total of 30 of all 39 urban Council areas over the 25-year time period (Appendix 7). Nine of these LGAs showed bandicoot presence across all time slices. Conversely, in nine LGAs the long-nosed bandicoot was absent across all time slices. See Table 1 for a summary of long-nosed bandicoot presence per 5-year time slice per LGA and Sydney region, LGA sizes and land use proportions per LGA.

Presence of long-nosed bandicoots in 1km^2 grid cells were mapped for each time slice (Maps 2-6). Similar to the analysis of the southern brown bandicoot, grid cells of long-nosed bandicoot occurrence within national parks were removed in the geospatial analysis process. Mapping shows bandicoot presence in eastern Sydney as very low with last sightings in Randwick in only two 1 km^2 grid cells likely indicating a small and dwindling population. This region of Sydney has a very small percentage of national park lands. The remaining two eastern LGAs (Woollahra and Waverley) show no sightings throughout the 25-year study period coinciding with approximately 50% land use categorized in these areas as urban-residential and a further 25 and 35% respectively described as industrial-commercial (intense development) and no national park land.

Within the inner west of Sydney bandicoot presence increases after 2003 coinciding with the discovery of this population and its subsequent listing in 2008. Grid cell occupancy rates remain similar in the next time slice, 2008 - 2013, but decline between 2013 and 2018 as does connectivity of occupied cells indicating potential fragmentation in this already small meta-population. Marrickville LGA shows occupancy in all time slices.

Land-use proportions in the inner west of Sydney again show very low proportions of national park lands (0.23 – 2.84%) and only occurring in five of the eleven LGAs in that region. Industrial and commercial lands are high ranging between 31 and 60% of all land in each of the 11 LGAs with the exception of Fairfield at 25%. The two LGAs with almost 50% land use described as industrial-commercial show no occupancy throughout the study period (Strathfield and Auburn).

In western Sydney occupancy again begin between 2003 and 2008 but at very low levels given the area of the LGAs and dwindling to only one grid cell in 2013-2018. Blacktown shows no occupancy throughout the study period despite small adjoining national park land (7%) and a large proportion of agricultural and rural land (34.52%). Long-nosed bandicoot presence is low in Parramatta and Penrith since its first appearance in 2003. Connectivity to national parks is low in Parramatta and

Blacktown however Penrith has reasonable connectivity with national park lands at just under 20% and a significant proportion of agricultural and rural land at 43%.

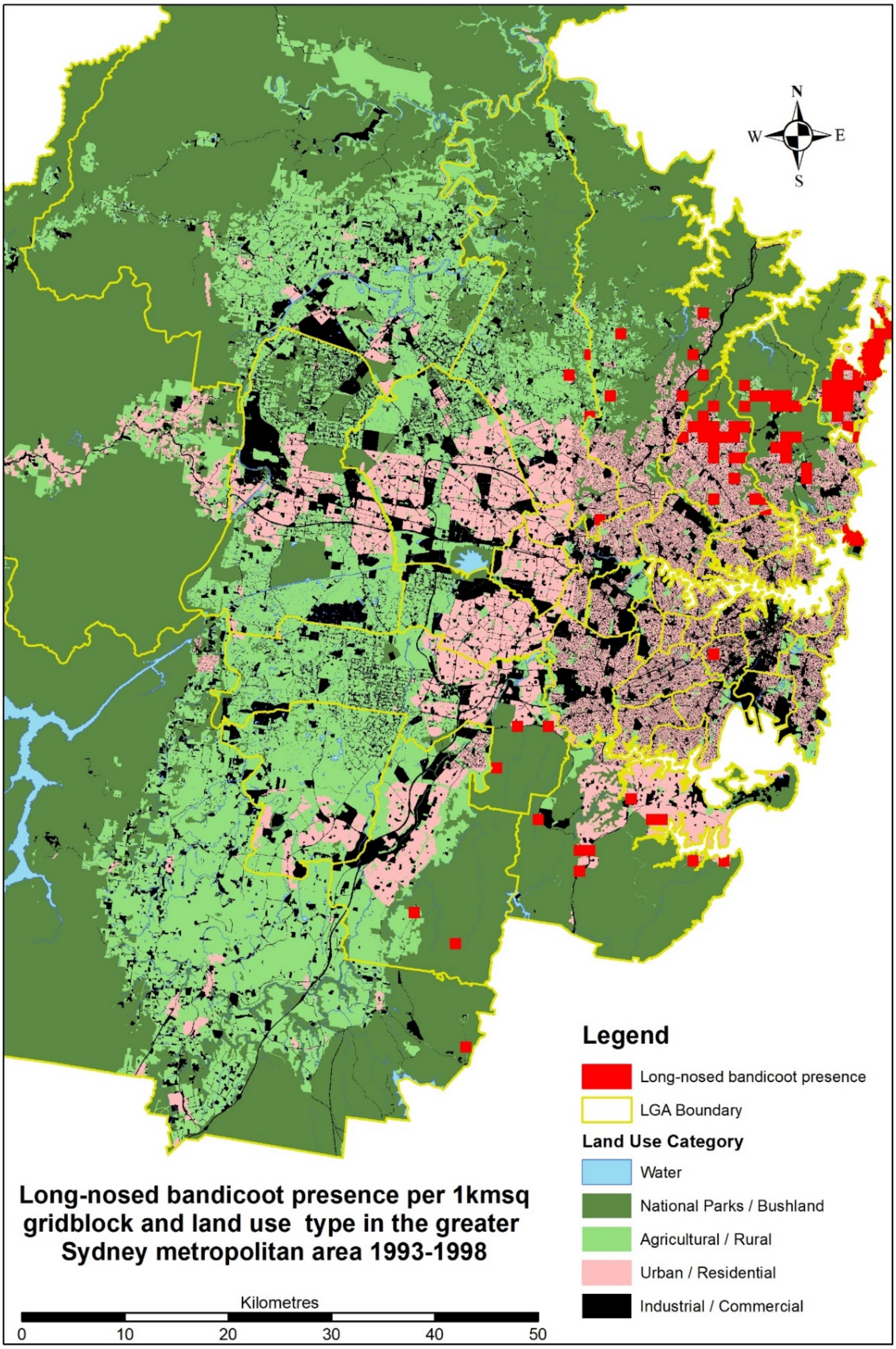
In Sydney's north-west, The Hills Shire LGA has low occupancy throughout the study period (given the LGA size at 400.48km^2) and 43% proportion of the LGA classified as national park and a further 33% as agricultural and rural land. The other LGA in this region, Ryde, shows low occupancy from 2003 – 2008 and 2008 – 2013 and no sightings between 2013 and 2018 with a small proportion of the LGA classed as national park (8.47%) and agricultural-rural (10%).

The south-western Sydney region consists of the largest total area in all urban Sydney (3,416.08km^2) and five LGAs. Bandicoot presence however is low throughout the region with no occurrences recorded in Camden. Liverpool has presence recorded only between 1993 and 2003 despite land uses of almost 25% national park land and 45% agricultural-rural land. Wollondilly has increasing occurrence recorded since 2003 and a very high proportion of national park in the LGA at 73% and agricultural-rural land of almost 20%.

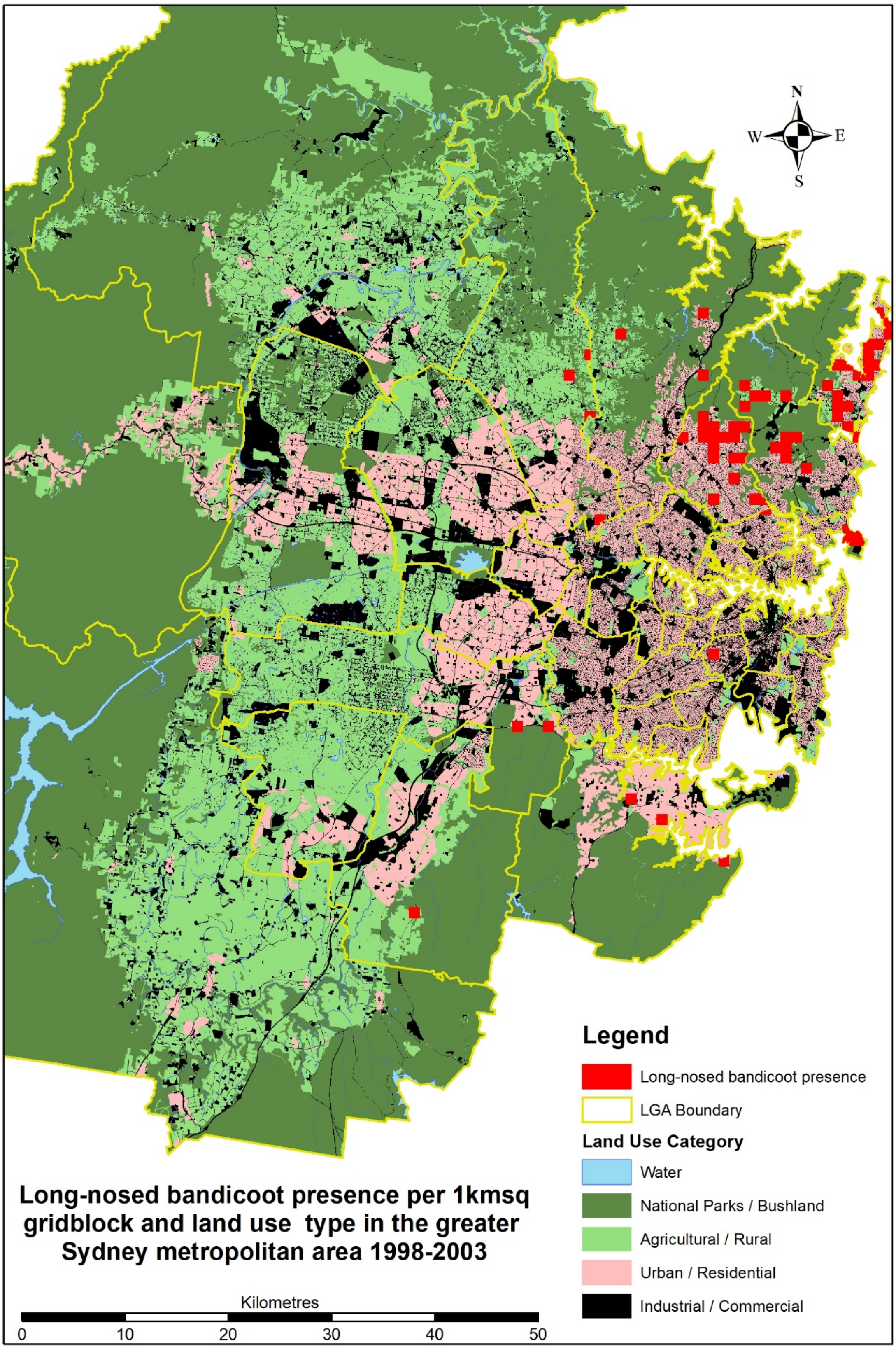
Southern Sydney has a total of five LGAs with three showing no occupancy throughout the study period (Hurstville, Botany and Kogarah), no lands classified as national parks and less than a maximum of 15% agricultural-rural land in any of these LGAs. Rockdale is similar in land use proportions and registers bandicoot presence in just grid cell in one time slice between 2003-2008. The contrast in this region is Sutherland Shire which demonstrates low bandicoot presence in all time slices but at decreasing levels since the first time slice 1993-1998. This LGA includes a very high proportion of national park at 71%.

The region of northern Sydney overall shows the most bandicoot presence. Across all time slices six of the ten LGAs in this region show occupancy throughout the study timeframe. Of these six LGAs all but two show relatively high proportions of national park land ranging between 32 and 72%.

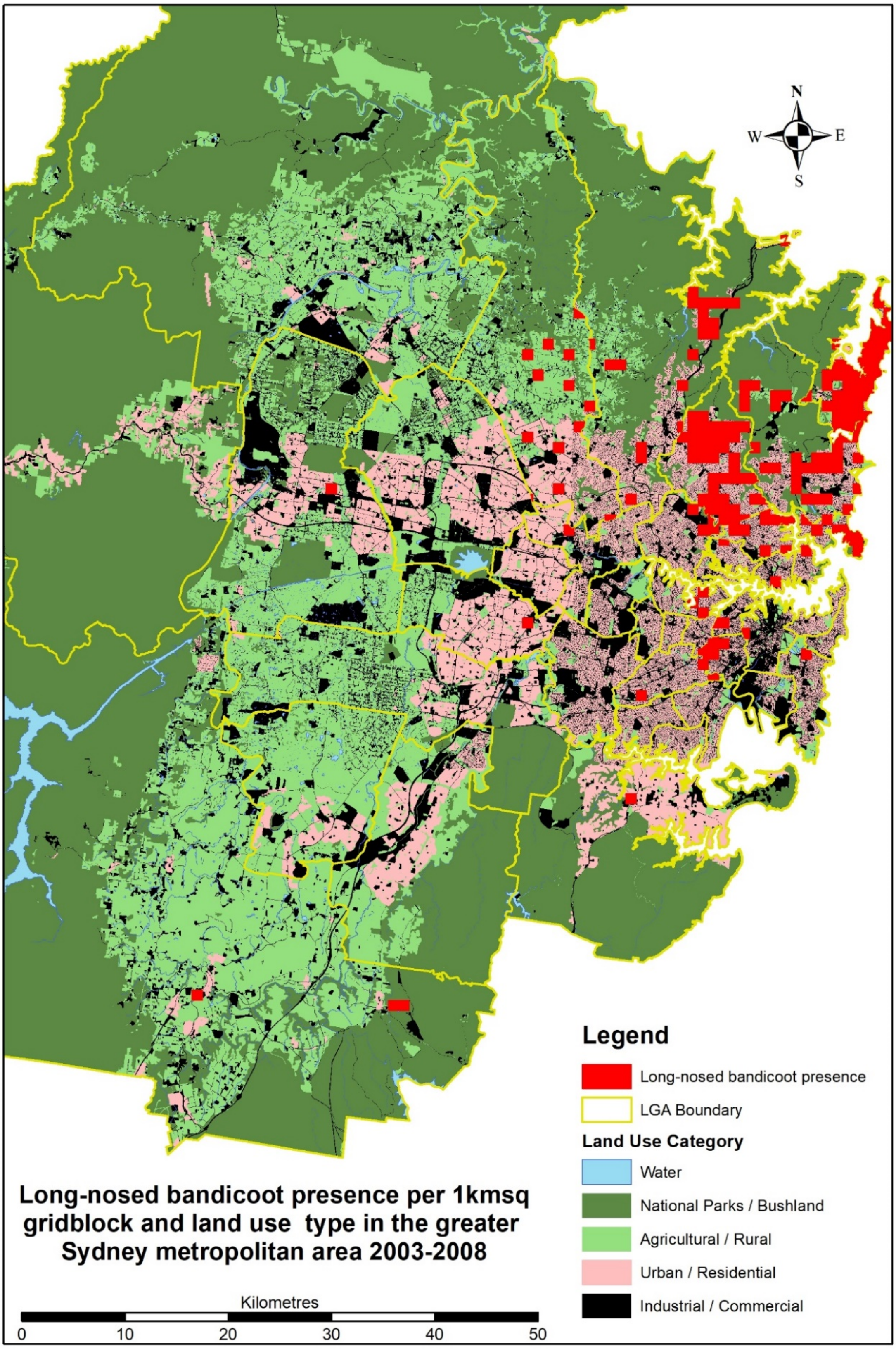
The remaining four northern LGAs closest to the city, Hunters Hill, North Sydney, Lane Cove, and Mosman show low levels of bandicoot occurrence since 2003 with Hunters Hill Council recording no bandicoots in any time slice and very low proportions of national park land (between 1 and 4%) Agricultural-rural land is present in all LGAs and ranges between 8% (Mosman) and 16% (Hunters Hills). See Table 1 for a summary of long-nosed bandicoot presence per 1 km^2 and land use proportions per LGA.



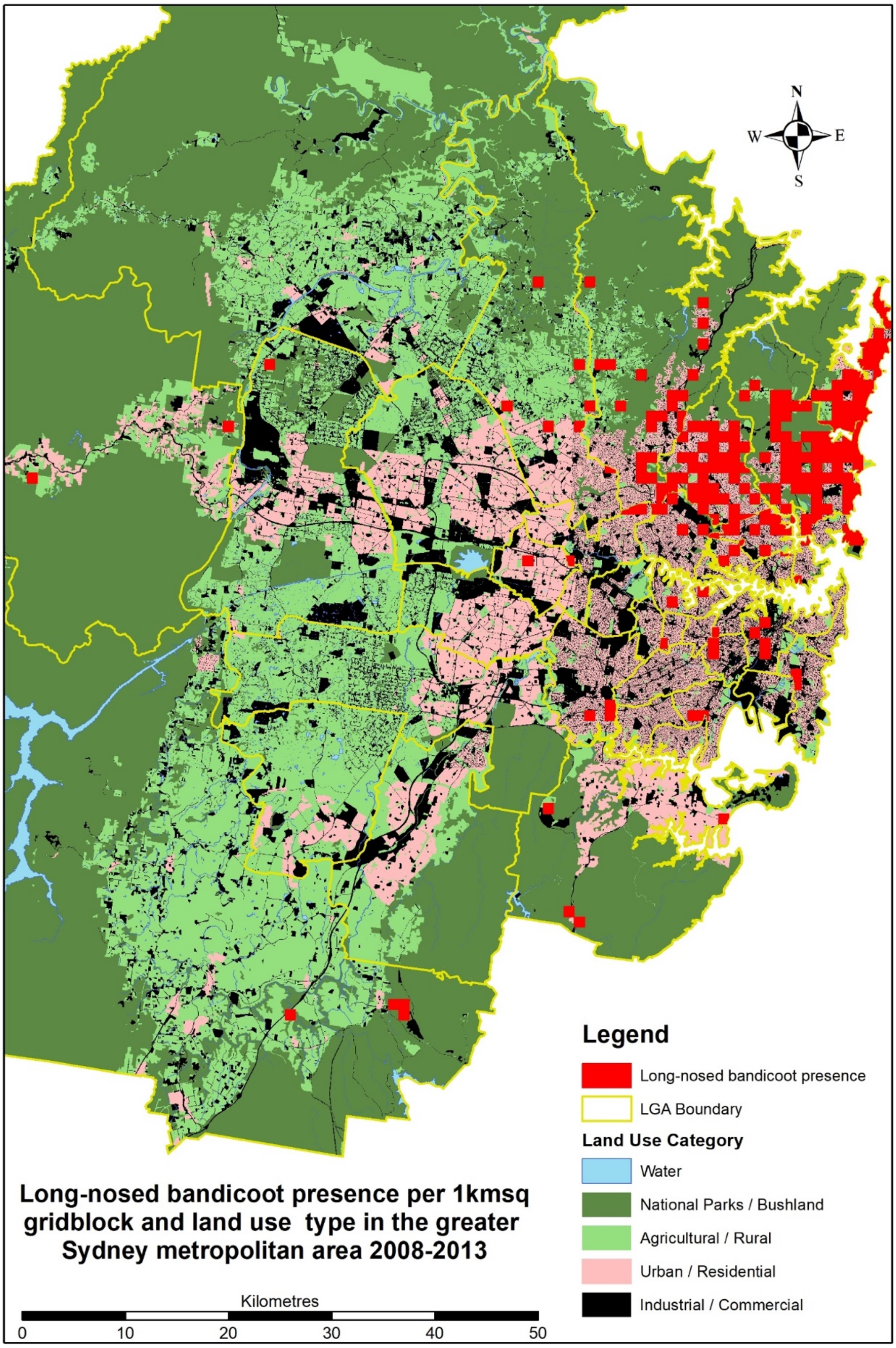
Map 2 – Long-nosed bandicoot presence in urban Sydney per 1 km^2 grid cell, land use category and LGA 01 September 1993 – 31 August 1998



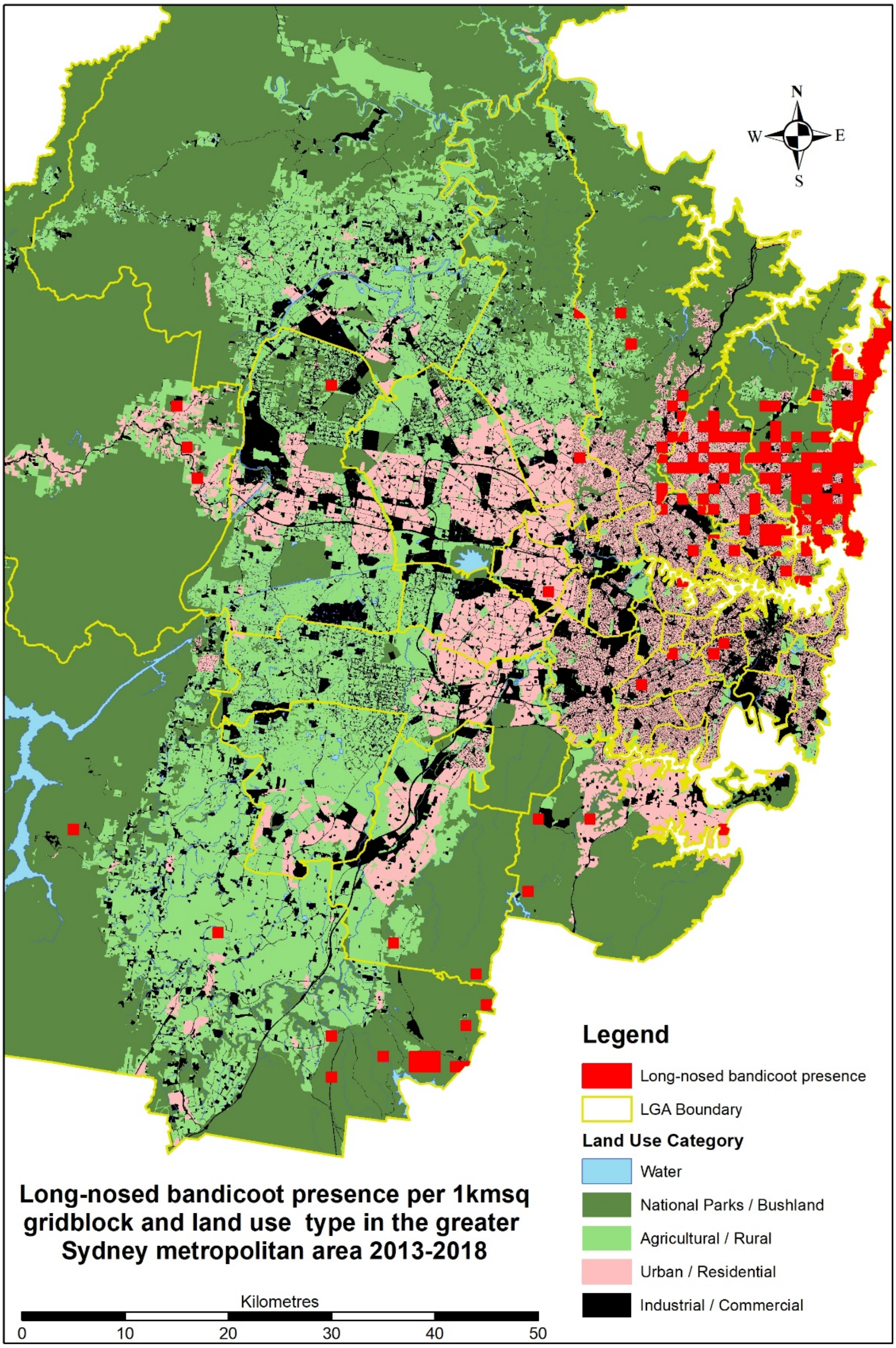
Map 3 – Long-nosed bandicoot presence in urban Sydney per 1 km^2 grid cell, land use category and LGA 01 September 1998 – 31 August 2003



Map 4 – Long-nosed bandicoot presence in urban Sydney per 1 km^2 grid cell, land use category and LGA 01 September 2003 – 31 August 2008



Map 5 - Long-nosed bandicoot presence in urban Sydney per 1 km^2 grid cell, land use category and LGA 01 September 2008 – 31 August 2013



Map 6 – Long-nosed bandicoot presence in urban Sydney per 1 km² grid cell, land use category and LGA 01 September 2013 – 31 August 2018

Table 1 – Long-nosed bandicoot presence by 1 km^2 grid cells per five-year time slice per LGA and proportion land use within each LGA

Region of Sydney (Area km^2)	Local Government Area (LGA) (Area km^2)	Bandicoot Presence in 1 km^2 grid cells by 5-year time slice					% LGA Water	% LGA Agricultural-Rural	% LGA Urban-Residential	% LGA Industrial-Commercial	% LGA National Park
		1993-1998	1998-2003	2003-2008	2008-2013	2013-2018					
Eastern (57.83)	Randwick (36.32)	0	0	**1**	**2**	0	4.01	24.94	34.29	35.29	1.43
	Waverley (9.24)	**0**	**0**	**0**	**0**	**0**	**0**	**12.02**	**52.27**	**34.05**	**1.64**
	Woollahra (12.27)	**0**	**0**	**0**	**0**	**0**	**1.31**	**14.88**	**52.5**	**25.92**	**5.36**
Inner West (361.83)	Ashfield (8.28)	0	0	**2**	**1**	0	0.51	6.36	58.23	34.9	0
	Auburn (32.47)	**0**	**0**	**0**	**0**	**0**	**2.07**	**22.97**	**25.01**	**48.34**	**1.61**
	Bankstown (76.80)	0	0	0	**3**	0	1.69	14.86	42.23	40.71	0.51
	Burwood (21.68)	0	0	0	1	0	0.17	5.79	61.16	32.88	0
	Canada Bay (19.82)	0	0	**3**	**2**	**1**	1.13	15.56	50.81	31.74	0.77
	Canterbury (33.56)	0	0	**3**	0	**2**	1.59	11.93	52.88	33.6	0
	Fairfield (101.53)	0	0	**1**	0	0	2.24	29.64	40.13	25.14	2.84
	Leichhardt (10.55)	0	0	**2**	**1**	0	2.53	9.14	41.65	46.69	0
	Marrickville (16.52)	**1**	**1**	**7**	**2**	**2**	**2.79**	**8.86**	**40.02**	**48.33**	**0**
	Strathfield (13.90)	**0**	**0**	**0**	**0**	**0**	**0.83**	**11.33**	**36**	**51.85**	**0**
	City of Sydney (26.72)	0	0	**1**	**4**	0	1.26	17.14	20.87	60.5	0.23
West (712.2)	**Blacktown (246.09)**	**0**	**0**	**0**	**0**	**0**	**3.1**	**34.52**	**29.93**	**24.85**	**7.61**
	Parramatta (61.36)	0	0	**1**	**4**	0	1.89	15.35	48.76	32.14	1.86
	Penrith (404.75)	0	0	**1**	**1**	**1**	2.83	43.41	11.5	22.39	19.88
North West (440.95)	Ryde (40.47)	0	0	**4**	**5**	**5**	0.52	10.21	44.83	35.96	8.47
	The Hills (400.48)	**4**	**4**	**13**	**7**	**2**	**2.46**	**32.96**	**11.1**	**9.64**	**43.84**
South West (3416.08)	**Camden (201)**	**0**	**0**	**0**	**0**	**0**	**2.69**	**69.57**	**9.19**	**16.24**	**2.31**
	Campbelltown (312)	**2**	**1**	0	0	**2**	1.4	30.97	12.88	10.46	44.28
	Holroyd (40.18)	0	0	0	**1**	**1**	0.89	10.74	54.16	33.49	0.72

Table 1 – Long-nosed bandicoot presence by 1 km^2 grid cells per five-year time slice per LGA and proportion land use within each LGA

Region of Sydney (Area km^2)	Local Government Area (LGA) (Area km^2)	Bandicoot Presence in 1 km^2 grid cells by 5-year time slice					% LGA Water	% LGA Agricultural-Rural	% LGA Urban-Residential	% LGA Industrial-Commercial	% LGA National Park
		1993-1998	1998-2003	2003-2008	2008-2013	2013-2018					
	Liverpool (305.49)	**3**	**2**	0	0	0	2.67	44.48	13	16.09	23.76
	Wollondilly (2557.41)	**1**	0	**3**	**4**	**15**	3.98	18.7	0.61	3.04	73.66
South	**Botany Bay (26.75)**	**0**	**0**	**0**	**0**	**0**	**3.2**	**14.82**	**16.99**	**64.99**	**0**
(426.82)	**Hurstville (22.72)**	**0**	**0**	**0**	**0**	**0**	**0.47**	**13.74**	**55.57**	**30.22**	**0**
	Kogarah (15.55)	**0**	**0**	**0**	**0**	**0**	**0.82**	**10.79**	**59.63**	**28.77**	**0**
	Rockdale (28.22)	0	0	0	**2**	0	3.13	15.21	44.18	37.47	0
	Sutherland (333.58)	**9**	**3**	**1**	**4**	**4**	**1.44**	**4.15**	**17.51**	**5.42**	**71.47**
North	**Hornsby (462.09)**	**6**	**3**	**21**	**27**	**9**	**1.36**	**11.54**	**8.12**	**6.43**	**72.56**
(859.21)	**Hunters Hill (5.71)**	**0**	**0**	**0**	**0**	**0**	**2.1**	**16.03**	**48.58**	**29.19**	**4.09**
	Ku-ring-gai (85.39)	**20**	**18**	**41**	**43**	**26**	**0.5**	**8.27**	**42.28**	**16.56**	**32.39**
	Lane Cove (10.48)	0	0	**1**	**3**	**1**	1.2	14.11	52.19	30.95	1.55
	Manly (14.35)	**4**	**4**	**9**	**6**	**17**	**1.52**	**11.63**	**38.24**	**26.23**	**22.17**
	Mosman (8.65)	0	0	**1**	**2**	**4**	2.05	8.87	47.42	25.3	16.36
	North Sydney (10.47)	0	0	**1**	**1**	**2**	0.19	14.34	45.98	37.56	1.93
	Pittwater (90.31)	**30**	**18**	**47**	**43**	**35**	**1.86**	**9.25**	**20.22**	**9.53**	**59.06**
	Warringah (149.33)	**17**	**12**	**33**	**64**	**57**	**2.15**	**9.44**	**17.02**	**13.26**	**58.11**
	Willoughby (22.43)	**1**	**1**	**10**	**13**	**9**	**1.06**	**11.07**	**47.46**	**29.95**	**10.46**
Total Area (6274.92)		**98**	**67**	**207**	**246**	**195**					

*LGAs shaded **green** show bandicoot presence in all time slices*
*LGAs shaded **red** show bandicoot absence in all time slices*

Influence of human population density and land use on bandicoot occupancy

Based on the literature I identified demographic and land use variables that I wanted to test for association with bandicoot presence: population, car ownership, housing density, road density, agricultural-rural, industrial-commercial, urban-residential, national park, and water. Prior to statistical analysis, variables were tested to check the quality and normality of our datasets. First, I ran a collinearity test and found that the demographic variables population, housing, road and car densities were extremely correlated (97%-100%) (Figure 2). As a result population data alone were selected for further analysis as it was deemed sufficiently representative of these four demographic variables.

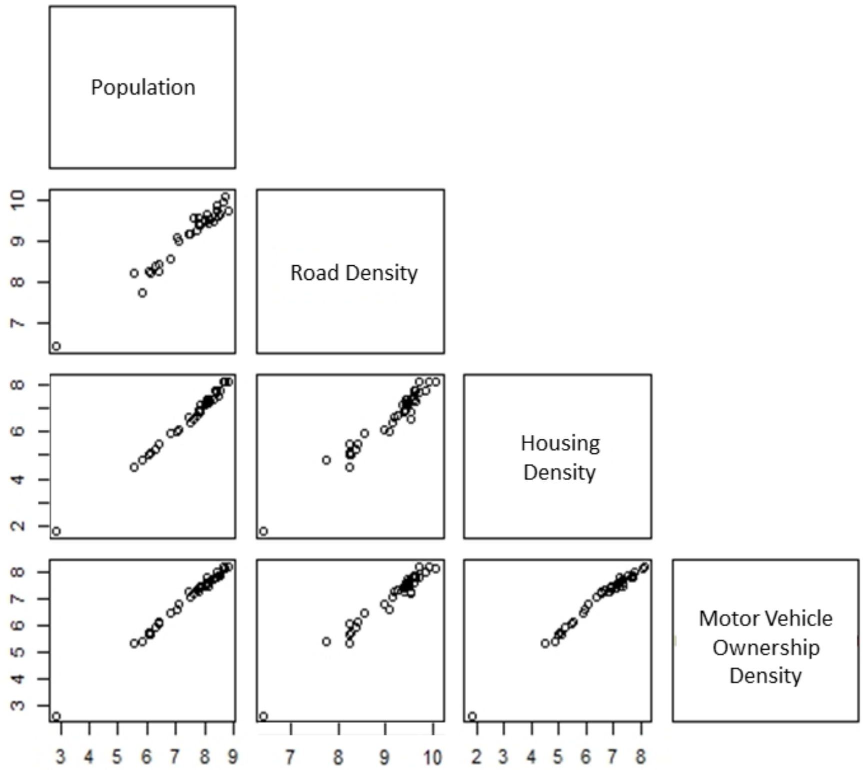


Figure 2 – Significant Collinearity demonstrated between demographic variables population, road density, housing density and motor vehicle ownership densities

Next, I performed the ‘qqnorm’ test on the differences in LGA sizes and LGAs over time to account for inconsistent survey effort and pseudo-absences to see if the necessary assumptions of linearity were sufficiently upheld. The data distributions for each category were sufficiently similar to the theoretical distribution suggesting these datasets were not skewed and therefore useable in further analyses (Figures 3).

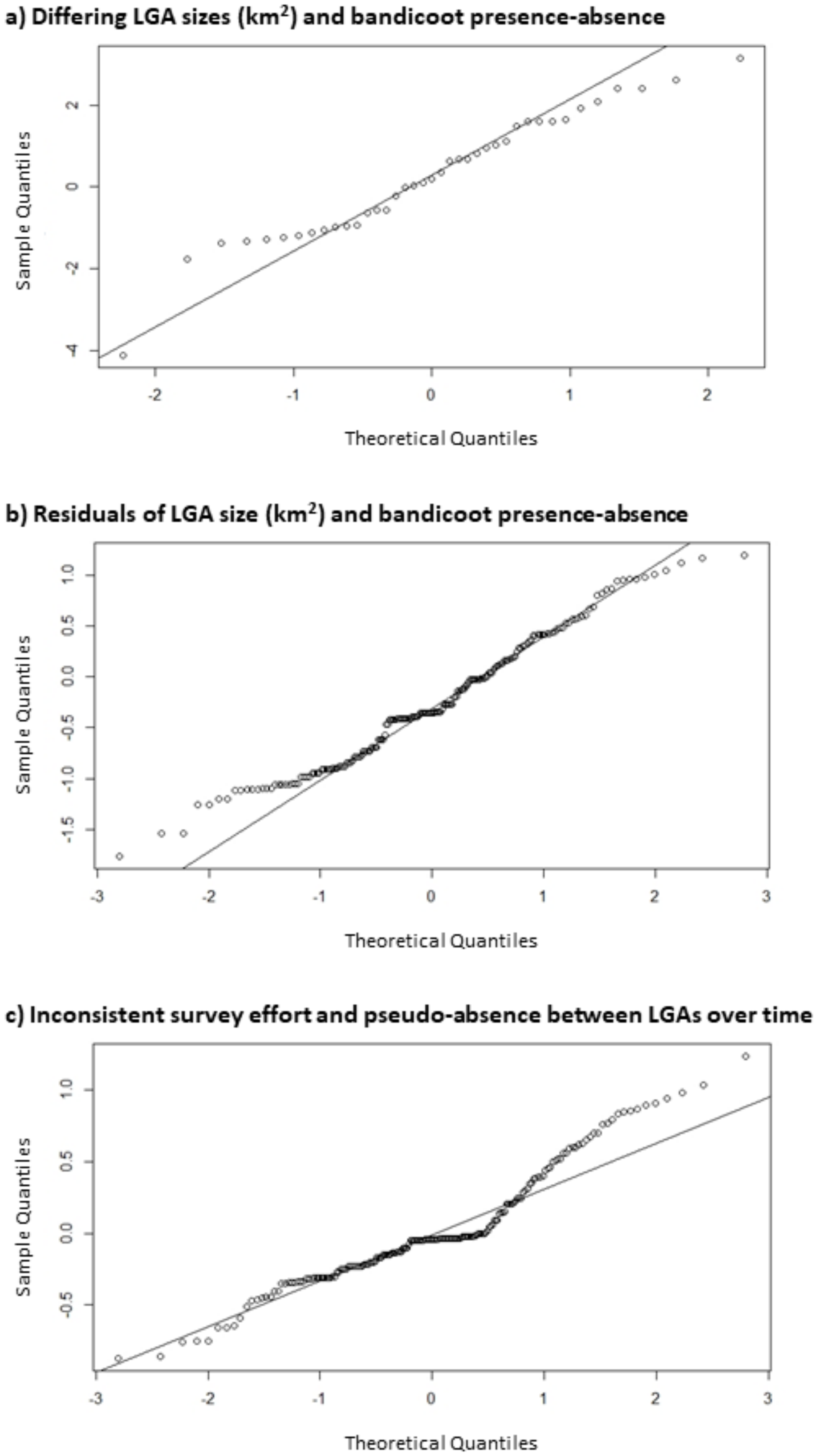


Figure 3 - Q-Q plots mapping the linearity of Random Effects of a) differing LGA sizes (km^2) and bandicoot presence-absence, b) Residuals of LGA size (km^2) and bandicoot presence-absence, and c) inconsistent survey effort and pseudo between LGAs over time. Data samples (◦) are plotted against quantiles calculated from a theoretical distribution. The straight line represents normal distribution.

Finally, I calculated the Simpsons Diversity Index between the five land use categories and the 39 LGAs to establish if there was sufficient heterogeneity for analysis. The four land use types were sufficient: national park agricultural-rural, industrial-commercial, urban-residential and national park. However, as the proportion of water in any one LGA ranged between 0% and 4% of land use this variable was removed from analysis.

To assess the relationship between bandicoot presence (occupied grid cells) and the remaining variables (population, agriculture-rural, industry-commercial, urban-residential and national park land use) I performed the generalized linear mixed effects model. Modelling of bandicoot occupied cells and population density datasets failed to converge suggesting more records are required to test this relationship.

Modelling of bandicoot presence-absence and agricultural rural land demonstrated a strongly negative relationship (-0.841) between bandicoot-occupied grid cells and increasing agricultural-rural land was found (p=0.00057) (Table 2 and Figure 4). The remaining land use variables, however, did not predict bandicoot occupancy (Figure 4) [Urban Residential (p=-0.314), Industrial-Commercial (p=-0.278), national park (p= -0.149)].

Table 2 - Summary of outputs of statistical analysis of random effects of LGA size and LGA over time for the predictor variable Agricultural-Rural *and* long-nosed bandicoot presence absence in all LGAs over all five-year time slices between 01 September 1993 and 31 September 2018

Random effects of LGA sizes over time and LGA			
Groups	**Name**	**Variance**	**Std. Dev.**
LGASby Time	(Intercept)	0.5581	0.7471
LGA	(Intercept)	3.0875	1.7571

Number of obs: 195, groups: LGAbyTime, 195; LGA, 39 where obs represent bandicoot presence or absence in 1km^2 grid cells for each LGA across all time slices

Fixed effects				
	Estimate	**Std. Error**	**z value**	**Pr (>|z|**
(Intercept)	-2.7039	0.6116	-4.421	9.82e-06***
Ag_Rural	-10.9877	3.1891	-3.445	0.00057

*Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1*

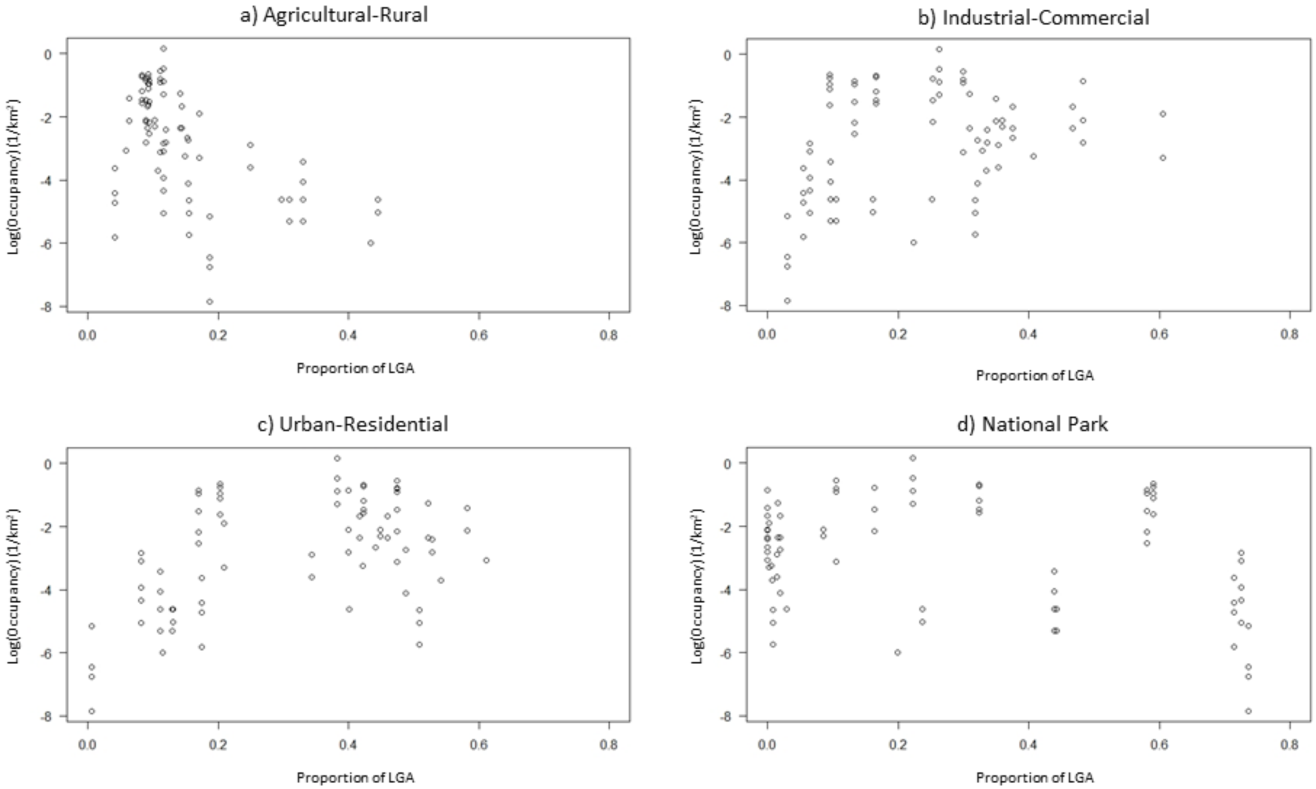


Figure 4 – Relationship between categorised land use and number of bandicoot-occupied 1 km^2 grid cells in an LGA 1993-2018

In each plot, the x-axis represents bandicoot presence per km^2 by LGA size and the y-axis represents the proportion of the LGA classified as a) agricultural and rural land, b) commercial and industrial land, c) urban and residential land, and d) national park land. Each LGA was analysed using both generalized linear mixed effects regression models (untransformed data and quadratic function) and is represented as a point (◦); i.e. 39 LGAs x 2 = 78 points.

DISCUSSION

In the intensifying urbanisation of Sydney, a deeper understanding of bandicoot ecology and behaviour is imperative for developing effective ESD plans to ensure bandicoot persistence. This study examined whether sufficient sightings, demographic and land use datasets are available and of a high enough quality for a desk-top analysis to potentially predict bandicoot presence in the Sydney urban landscape and what information could be gained from this analysis of southern brown and long-nosed bandicoots in Sydney.

Two key results came from this project:

1) Although currently limited, with improvement, these datasets *can* provide insight into bandicoot presence using desk-top analyses, as evidenced by
2) The strongly negative effect of increasing agricultural and rural land (open green space) on bandicoot occurrence.

This study highlights the need to improve the datasets necessary for this type of analysis. The lack of baseline information has serious implications for policy and planning agencies if we are to be serious about preserving bandicoots in Sydney in the face of large-scale population rise and development. The lack of readily accessible aggregated biological data for the management and research of biodiversity is already recognised (Alluvium, 2016, La Salle et al., 2016, Schwartz A., 2014) as this has significant implications for management and persistence of all native fauna (including bandicoots) in both urban and bushland settings.

Geospatial Data and Modelling

Geographical information systems and statistical packages are sufficiently powerful to handle these types of examination. The two software packages used in this study for mapping (ArcGIS) and statistical analysis (R) have recently collaborated, producing a system entitled the 'R-ArcGIS-Bridge' that is capable of mapping and undertaking statistical analysis at the same time (Environmental Systems Research Institute (ESRI), 2018). Further development of this partnership could provide a very powerful tool for researchers and conservation biologists provided high quality land use models and demographic datasets are available.

Land use modelling in this study was based upon aerial imagery created by the NSW OEH over the period 2003 – 2012. Although this data were sufficient for analyses, this broad snapshot of Sydney urban land use is no longer current and may have affected the quality and reliability of the analysis.

The development of readily-updatable land use models that capture land use change over time would be a significantly more powerful tool for researchers and planners. The recent advent of mapping systems, such as NearMap with approximately ten years of very high-resolution satellite data updated in urban areas, including Sydney, every two months, may make this type of analysis possible in the future (NearMap, 2018). The Greater Sydney Local Lands Services (GSLLS) has recently released the 'Sydney Green Grid' spatial framework and GIS dataset that combines hydrological, agricultural, recreational and transport mapping data of Sydney's green landscape and corridors which may also prove a useful tool for future biodiversity researchers (Greater Sydney Local Lands Services, 2018). The use of this dataset in this study was not feasible due to the timing of its release in relation to this study.

Insights from collated data

Bandicoot Sightings

This project combined recorded bandicoot sightings data from five sources including government databases and volunteer services. The study provides important insight into the currently patchy and limited records available in the ALA and Bionet and highlights the value of wildlife volunteer records in the urban space.

The lack of sightings recorded in the urban landscape is perhaps unsurprising as formal surveys on bandicoot persistence in Sydney have largely focused around the southern brown in its last known locations within national parks and the two listed long-nosed populations in Manly (Cumberland Ecology, 2018) and the inner west (Price, 2016).

Records from government databases, the ALA and Bionet, that cover over 50 years, were low. Initial queries indicated ~10,000 records for each database, however after cleaning only 14% and 19% of records remained in ALA and Bionet, respectively. From comments from Council bushland and biodiversity management officers the recording of local native flora and fauna and the use of Bionet and the ALA is limited or not utilised in some LGAs.

The lack of unique records and inconsistent survey effort makes baseline data about species presence and absence uncertain over both space and time and in turn makes meaningful statistical analysis difficult to achieve or the results untrustworthy. A lack of true-absence in any study reduces statistical power and can cause incorrect conclusions to be drawn and biases in parameter estimations (Hyun, 2013). In the rapidly growing and intensifying urban Sydney landscape these data are fundamental to analysis and planning for the conservation of bandicoots and other native fauna.

I recommend that Councils gather and record fauna sightings within both bushland and urban lands under their management and develop citizen science monitoring programs with local residents to gather fauna sighted on private lands and ensure these are uploaded into Bionet regularly.

The use of urban wildlife rescue records were very useful to this study and it is hoped a more detailed evaluation of this data may be undertaken by other researchers to ascertain it's value to future studies. Communications with OEH staff throughout this project reveals that the value of wildlife rescue data has been recently recognised by the state department and a project is currently underway to clean and upload volunteer rescue data from the 28 volunteer wildlife groups operating across NSW into Bionet (2003-present). Once cleaned, this effort could provide over 100,000 new records into the database although it must be remembered that no matter how great the dataset, without ground-truthing, the issue of absence remains problematic. The estimated release date for these data is currently 2019. It is unfortunate that WIRES (Sydney) bandicoot records could not be used in this study as they may have increased the sample sizes to a degree that the generalised linear models were able to converge and better test our hypotheses about population and the land use variables that affect bandicoot presence.

Wildlife rescue volunteers are adept in the identification of native fauna. This sector has been operating for 30-40 years in NSW and has developed significantly over that period. Wildlife volunteers undertake detailed training of species encountered in their area of operation and are adept in the identification of native species, including bandicoots. Bandicoots are prone to stress in captivity and their young are difficult to rear. They are therefore cared for by experienced rehabilitators who often reside in areas where bandicoots naturally occur so can readily identify the species (Elwood, pers obs, 2018). Under the newly introduced NSW Biodiversity Conservation

Act 2017 this sector is now working with the NSW OEH to move towards accreditation-based training (New South Wales Office of Environment and Heritage, 2016b). This study has provided an initial indication of the usefulness of such data and it is hoped they will become better incorporated into wildlife monitoring and recovery programs in future.

Demographic Data

Data availability and quality proved an issue for the use of demographic variables. Further, the high collinearity between these variables led to the inclusion of population density only, with the subsequent analysis failing to converge and reported results unusable. Census information provides a snapshot only of demographic conditions every five-years and is not available in digital form prior to 2006. Council amalgamations in May 2016 also mean datasets before and after that time use differing LGA boundaries. To achieve a meaningful statistical analysis using population records and to demonstrate change over time (e.g. annually) it is necessary for researchers to construct digital data files from census population data reported in non-digital formats.

Similarly, should the impacts of changing housing or motor vehicles densities be a research focus, a similar process would be required. The development of readily accessible, reliable and detailed demographic and environmental datasets would be of great benefit to researchers (Belbin and Williams, 2016, MacMillan and Marshall, 2006, Wegner et al., 2005).

Pet ownership data

Predation by cats and dogs is a known impact on bandicoot dispersal and persistence (New South Wales Office of Environment and Heritage, 2016a).

Unfortunately, querying census information about pet ownership levels revealed no digital data were available to investigate this variable. A survey of the Companion Animals Register (with appropriate human ethics approval) may make estimates about this feasible for future studies. Although this would not provide information about predation levels by domestic animals it would provide insights as to the densities of cats and dogs residing in areas where bandicoots also occur. A query of wildlife rescue data as to the cause of injury to rescued bandicoots may also provide some information about predation levels by domestic animals.

The long-nosed bandicoot appears to be reasonably tolerant of cats and dogs and is known to opportunistically take advantage of left out pet food without obvious fear (Elwood, pers. obs., 2018, Hillman et al., 2017, Scott et al., 1999). The underlying reason for this tolerance is unknown but it has been suggested that this relates to either naivety or habituation (Carthey and Banks, 2012). A more recent study suggests that long-nosed bandicoots on mainland Australia, having co-existed with dingoes, may recognise dogs but not cats (Frank et al., 2016). This recognition coupled with the frequency with which dogs may be encountered in the urban matrix may have endowed urban populations with a greater tolerance and habituation to these animals. The keeping of cats indoors at night for the protection of many nocturnal native species, including bandicoots, has been recommended by several commentators for some time (Royal Society for the Prevention of Cruelty to Animals, 2018) and is a growing practice (Lilith et al., 2010).

Data availability - exotic predators

Although beyond the scope of this study predation by non-domesticated exotic species such as foxes and cats is highly relevant to bandicoot persistence. Urban fox abundance and predation rates are difficult to measure (Ramalho et al., 2018). To gather some baseline data on this key threatening process future studies could include an enquiry of Councils as to the numbers of foxes controlled as part of their feral animal control programs and locations of fox sightings reported to Council by residents. In northern Sydney, twelve Councils and several other land managers including State Forests NSW, Sydney Electricity, Sydney Water and the NSW National Parks and Wildlife Service have been conducting coordinated fox control programs for almost 20 years (Sydney North Vertebrate Pest Committee formerly the Urban Feral Animal Action Group). In Sydney's inner west and southern suburbs, coordinated fox control programs became established and coordinated in 2015 with the long-nosed bandicoot cited as one of the key species (among others) requiring protection (Hoh, 2016, Great Sydney Local Land Services, 2018). A second line of enquiry into FoxScan (a division of FeralScan), an online system started in 2009 for the reporting and recording of fox sightings and other exotic invasive species Australia-wide could also be useful (New South Wales Department of Primary Industries, 2009). Again, these figures would not provide direct information about levels of fox predation for bandicoots but may provide enough data for coarse predation estimates to be calculated.

Conclusions re Data Availability and Quality

Southern brown bandicoot

A lack of records of the southern brown bandicoot prevented statistical analysis in urban Sydney. Only 10% of reported sightings for the past 25 years were in areas other than national park land.

Mapping the southern brown bandicoot sightings identified recorded occurrences of this species in urban areas is strongly associated with proximity to national parks or remnant bushland (Map 1).

The lack of records in the urban matrix is not unexpected and may be due to survey effort as the majority of records for this species over the past 25 years came from surveys guided by state directives as part of the Fox Threat Abatement Plan that targeted Ku ring gai and Garigal National Parks in Sydney's north and the Royal National Park in Sydney's south (New South Wales Office of Environment and Heritage, 2008) and as part of ongoing monitoring required in the southern brown's recovery plan (New South Wales Department of Environment and Conservation, 2006). However, given that most of the urban long-nosed bandicoot sightings reported in this study resulted from citizens and/or wildlife rescue groups, it seems that if southern browns were present in urban areas, they would be detected by these same methods. Therefore, it seems it can be concluded that southern brown bandicoots are not urban adapters in Sydney, unlike long-nosed bandicoots appear to be.

This may be due to key aspects of southern brown bandicoot behaviour – for example, recent studies demonstrate that southern browns are more abundant in modified and peri-urban landscapes that retain vegetation with reasonable structural connectivity, including weeds, even if close to urbanised areas in Melbourne (Victoria) (Maclagan et al., 2018, Maclagan, 2016) and in Tasmania (Daniels and Kirkpatrick, 2012). In Perth the southern brown struggles to persist in urbanised landscapes and rapidly becomes isolated, existing in small meta-populations seemingly unable to disperse amongst the matrix of housing and roads should vegetative corridors between habitat patches not be maintained (Ramalho et al., 2018).

The southern brown bandicoot's conservation status was reviewed in 2016 and has remained listed as endangered under the recently enacted NSW Biodiversity Conservation Act 2016 (New South Wales Office of Environment and Heritage, 2016a). A Recovery Plan for the southern brown developed in 2006 (New South Wales Department of Environment and Conservation, 2006) and nationally in 2010 (Brown and Main, 2010) identifies that the key threatening processes for this species include predation by introduced carnivores such as foxes (Coates and Wright, 2003, Claridge et al., 1991), cats and dogs (Dowle and Deane, 2009), habitat loss and fragmentation (Rees and Paull, 2000), and inappropriate fire regimes (Braithwaite, 1983),(New South Wales Office of Environment and Heritage, 2016a, New South Wales Department of Environment and Conservation, 2006). These threats are all relevant in its habitat in Sydney.

In Sydney, the occurrence of this species is correlated with sandstone and woodland heath (Dowle, 2012, Atkins, 1998).This vegetation community has a prescribed ecological burn time of between 8 and 25 years (NSW National Parks and Wildlife Service, 2004) but is often burnt more regularly as part of hazard reduction programs in urban areas for the protection of homes and public safety and has been cited as a potential threat to their persistence (New South Wales Department of Environment and Conservation, 2006). Should burning be required for ecological reasons or hazard reduction, this should be undertaken in a mosaic fashion to ensure shelter is still available for this species.

The southern browns inability to penetrate the Sydney urban space may also include behavioural aspects such as a pre-disposed intolerance and/or lack of habituation to predators such as cats, dogs, and black rats (Reigel, 1996), human activities and disturbance, either due to naivety, shyness and/or an inability to adapt to new conditions quickly. It is also possible the southern brown prefers denser cover for shelter than other Peramelid species such as the long-nosed. It has also been postulated that due to climatic conditions this species may have suffered a significant range contraction due to climatic shifts in Australia well before European colonisation and thus may already have been largely restricted to heath in Sydney (Paull et al., 2013).

Finally, perhaps it is a combination of all or some of the factors outlined above *along with* direct competition with the long-nosed bandicoot itself that has limited the southern brown’s range in Sydney. Although these species have been observed living sympatrically (Dowle, 2012, Atkins, 1999, Opie, 1990) and certain factors affecting the two have been compared (Dowle, 2012), it seems the degrees, if any, of habitat and resource partitioning between the two species, has not been fully quantified.

The future for the southern brown in Sydney is uncertain. Surveying continues in previously known locations and it is possible they are still present in other undiscovered areas within national parks, but it is likely they will never penetrate the urban space and thus must be carefully managed according to the national and state Recovery Plans to ensure their ongoing persistence. This species may also benefit from wider surveying in similar habitats within these national parks to ascertain if other meta-populations are indeed present.

Long-nosed bandicoot

If taken at face value, the mapping of long-nosed bandicoot presence may lead one to conclude that prevalence of this species, particularly in northern urban Sydney, may have increased over time and that populations appear relatively stable in areas near national parks. However, this cannot be assumed as unknown and variable survey effort and reporting is likely between LGAs over the differing time slices and may be affecting the data analysis. For example, comments from Council staff in former Warringah, Manly, and Pittwater all confirmed at least annual submissions to Bionet whilst other LGAs were unable to confirm this.

One may conclude however, that unlike the southern brown bandicoot, the long-nosed bandicoot is a better urban adaptor, due to the number of occurrences in the same period in urban areas adjoining national parks where the southern brown is also present. Interestingly, while most occurrences of the long-nosed bandicoot are associated with LGAs with close proximity to national park land, the meta-population in former Pittwater LGA's relatively isolated Barrenjoey Headland may be considered an exception and worthy of further research as to what conditions make this part of the urban matrix so advantageous for bandicoots.

Some bandicoots species are recognised as urban adapters (Ramalho et al., 2018). Their persistence in some parts of the urban environment in Sydney and other Australian cities such as Brisbane and Tasmania appears due to their ability to exploit features that give them an advantage such as open foraging spaces such as lawns and parks (Hughes and Banks, 2011), a generalist diet able to consume supplementary or human food resources such as pet or discarded food waste (Scott et al., 1999, Dowle, 2012), in Brisbane, (FitzGibbon and Jones, 2006), in Perth (Hillman et al., 2017) and Melbourne (Maclagan, 2016), or more abundant natural food sources e.g. insects and access to artificial water sources (Maclagan et al., 2018). It is also possible in urban areas that the moister, human-modified urban soils may provide a more consistent and abundant supply of invertebrates. The long-nosed bandicoot's apparent bolder temperament and more plastic behaviour or levels of habituation may also mean they are quite tolerant of other exotic species found in areas heavily modified by humans such as the black rat *(Rattus rattus)* and dogs (Frank et al., 2016, Coates and Wright, 2003).

These features combined with the ability to breed all year round in favourable conditions, short gestation periods (Lyne, 1974, Stodart, 1977, Lyne, 1964, Heinsohn, 1966) and high fecundity (Scott et al., 1999) give the long-nosed bandicoot distinct advantages for persistence in the urban matrix (Fitzgibbon et al., 2011).

More comprehensive studies of the distribution of long-nosed bandicoots in urban Sydney to resolve presence-absence issues and inconsistent survey efforts would be a useful basis for further research as would case studies of differing urban meta-populations and an assessment of what factors may provide optimal conditions for their persistence in the urban matrix.

Increasing agricultural and rural land negatively impacts bandicoot presence

My analysis suggests that long-nosed bandicoot occurrence decreases significantly in increasingly agricultural or rural land (Figure 3). The mapping also suggests occurrence decreases in highly urbanised LGAs within the inner west, the eastern suburbs and northern regions with closest proximity to the city and little or no national park land.

Interestingly, our results statistically demonstrate what has long been observed and postulated by other researchers – that the long-nosed bandicoot readily takes advantage of open green spaces, such as lawns and parks or indeed agricultural and rural lands, for foraging *provided* there is sufficient vegetative cover available for shelter (Ramalho et al., 2018, Stirnemann et al., 2015). It is possible however that this result may be driven by "survey effort" – i.e. there is a much lower human population density in rural and agricultural areas, making sightings less likely than they are in more densely populated LGAs. Surveys of those LGAs with high proportions of agricultural-rural LGAs such as those in the south and north-west of Sydney (e.g. Liverpool, Campbelltown, Hurstville, Wollondilly and The Hills Shire) would identify if survey effort was indeed affecting this analysis and would be timely given the amount of development proposed in these areas in the coming years (Greater Sydney Commission, 2018). Anecdotally, personal communications with Council biodiversity staff in some LGAs indicated they believed the absence of bandicoot sightings in their area reflects true-absence. However, without further empirical surveys it is not possible to draw these conclusions.

Urbanisation and preserving bandicoot presence – ideal and current practice

Although only preliminary data, the relationship between bandicoot presence and agricultural-rural land suggests that preserving or creating appropriate vegetative cover such as remnant bushland and habitat corridors should play an integral part of future urbanisation development and infrastructure planning. The value of retaining, restoring and enhancing small habitat patches and corridors within urban areas for conserving bandicoots (and biodiversity) is well recognised (Bryant et al., 2017, Adam, 2004). Yet in Australia preference is often given to preserving larger bushland areas whilst smaller patches are sacrificed for development (Wintle et al., 2018).

For example, over 50 years ago the Rockdale Wetland Corridor was earmarked as a future freeway (Adam, 2004). Although formerly undervalued (Boon and Research, 2012), wetlands are now recognised by scientists worldwide as areas of significant ecological value (White,2012). Despite this it is possible this significant wetland corridor could be developed as part of the proposed F6 freeway extension currently under investigation by the Roads and Maritime Service (Martin, 2017).

Approximately 30 years ago, the historical Brundtlandt Report entitled *'Our Common Future'* published in 1987 and the subsequent United Nations Earth Summit in 1992, brought the terms 'biodiversity', 'ecological sustainable development' (ESD) and the 'Precautionary Principle' to the forefront as nations across the globe acknowledged, for the first time, that environmental degradation and biodiversity loss could be seen not only at national but global levels (World Commission on Environment and Development, 1987). This spurred on many countries to develop and introduce legislation to protect the environment and biodiversity and research institutes worldwide to incorporate these ideas into education. Australia was no exception, with a vast continent of unique wildlife, the NSW Endangered Fauna (interim protection) Act 1991 was revised and became the NSW Threatened Species Act 1995. Further legislation such as the Commonwealth Environmental Protection and Biodiversity Conservation Act 1999 and the NSW Native Vegetation Act 2003 followed along with the development of State Environmental Planning Policies that saw, for the first time, native flora, vegetation communities and fauna identified, quantified, and declining species and communities listed as threatened. This legislation also provided a framework to identify what are now known as Key Threatening Processes (KTPs) and to develop Threat Abatement Plans (TAPs), monitoring and recovery programs. The NSW Native Vegetation Act introduced in 2003 bestowed greater assessment criteria and limitations on the clearing of bushland on private.

However, something appears to have changed in the early 21st century: 'ecologically sustainable development' has become 'sustainable development', the Precautionary Principle has become less quoted and somehow it seems biodiversity and environmental considerations may be taking a back seat. A growing number of commentators are voicing concern, not only in Australia, about the conservation and management of biodiversity in growing cities (Soga et al., 2014).

In NSW, this change in perspective is reflected in the more recent schemes and legislative amendments that have been introduced in the last 15 years. Examples include the introduction of the Biobanking and Bio-certification scheme in 2016, whereby developers can offset environmental damage or localised extinctions caused by their development by protecting other threatened species or vegetation communities elsewhere, amendments to the NSW Environmental Planning and Assessment Act 1979 in 2012 that saw the introduction of State Significant Development (SSD) and State Significant Infrastructure (SSI) effectively reducing the levels of environmental impact assessment required for major development and infrastructure projects and the minimised ability for local government authorities and communities to provide comment, giving the NSW Planning Minister the ultimate right of consent.

In 2015 the NSW Rural Fire Act 1997 was amended to include the '10/50 Vegetation Clearing Code of Practice for New South Wales' which gives private landowners the right to remove trees within 10 m of their home and clear understorey vegetation within 50 m of their home. This alone could have significant impact on bandicoot habitat and persistence in urban areas and has been widely criticised as open to abuse (Environmental Defenders Office, 2016).

In 2017, the enactment of the NSW Biodiversity Conservation Act 2016, and consequent repeal of the NSW Threatened Species Act 1995 and Native Vegetation Act 2003 and modifications to the Biobanking and Bio-certification scheme, has raised great concern from scientists and environmental organisations that the new legislation no longer affords enough protection to biodiversity, allowing land clearing by 'self-assessment' on private land including areas of threatened flora, fauna and communities, and that the biobanking and bio-certification scheme is now too weak to provide sufficient off-setting to prevent biodiversity loss (Total Environment Centre, 2018, Better Planning Network, 2017, Environmental Defenders Office, 2016, Bekessy et al., 2010).

Time will tell if newly enacted legislation and current ongoing practice are synergistic or discordant with the principles of ecologically sustainable development.

CONCLUSION

So what does all this mean for the future persistence of the long-nosed bandicoot in Sydney's rapidly growing urban landscape?

Firstly, a comprehensive analysis is limited without accurate and complete baseline data as to bandicoot presence and absence in Sydney. This will require systematic surveying and a greater and more regular reporting and use of Bionet by Council officers to assist in the development of management plans for this species.

The introduction of citizen science and biodiversity education programs in local Council areas (similar to the state program WildCount (NSW Office of Environment and Heritage, 2018b)) may also help gather records in the urban space on private lands and provide opportunities for urban residents to reconnect with their local flora and fauna. This may raise greater awareness of bandicoots and other native fauna struggling to persist in the urban matrix.

Digital datasets of demographic and land use variables will also need to be up-to-date, complete and accurate for generating baseline data and for analyses for future planning. The incorporation and analysis of datasets relating to both domestic and feral predators, beyond the scope and timing of this study, would also be valuable.

Once the datasets have been improved, repeating the analyses in this project should be undertaken to further assess the validity of the effect of agriculture-rural areas on long-nosed bandicoots and to reassess if any other variables predict bandicoot presence. An analysis of proximity measures to nearest bushland or national parks could be undertaken using higher resolution mapping datasets to quantify the types and density of surrounding vegetative cover, corridors and impediments to dispersal or migration, such as roads or areas of intense development between bushland or national park or identify urban persistence outside proximity to national parks or bushland. This analysis could be corroborated with NearMap data to incorporate expanding urbanisation. Finally, comparative studies between national park population abundance and home range sizes and those of urban exploiting bandicoots could also be investigated

It is the writers opinion that current planning policy and development practices are discordant with strategies that would facilitate bandicoot persistence.

The NSW Government Greater Sydney Commission's 2018 'Greater Sydney Regional Plan - A Metropolis of Three Cities' outlines where infrastructure, transport and development will be undertaken in the next thirty years to cater for a further 3.5 million people. This largely falls in undeveloped / rural lands in south-western, western, and north-western Sydney. An associated plan by the NSW Government Architect 'Sydney Green Grid' released in 2017 outlines opportunities for the creation, enhancement and management of green space in Sydney. Whilst both these documents suggest that biodiversity are a consideration, there is little, if any, detail as to how the conservation of native species, including the long-nosed bandicoot will be achieved.

It is unknown as to whether the Sydney Green Grid aims to extend the former plans of such organisations as the Sydney Metropolitan Catchment Management Authority or the Sydney Regional Organisation of Councils 'Sydney Green Web' that had similar aims. An assessment should be undertaken as to the success and extent of these previous projects and what could be improved and furthered in this undertaking.

Given some of the characteristics of the long-nosed bandicoot as described earlier such as their generalist diet, a boldness or plasticity in behaviour, and tolerance or even advantage in some urban landscapes, high fecundity and year-round breeding potential, a real opportunity exists to ensure long-nosed bandicoot persistence and even expansion into areas where range has been lost or into new areas where suitable habitat is created.

It is hoped any development, whether for housing, infrastructure or transport, will not commence until sufficient baseline data as to species presence and absence has been gathered. From these, plans can then be made that can optimise their persistence.

Where they are found to be present, development assessment at either a local government scale or for larger urbanisation plans should include surveying for bandicoot burrows and nests in order that, once identified, they may be preserved.

Ultimately development plans should facilitate long-nosed bandicoot requirements such as the preserving of bushland and understorey and the establishment or enhancement of habitat corridors and islands to address any existing issues of fragmentation and consideration given to their re-introduction in areas where they may already have been lost.

These urbanisation plans will need to be innovative and should include such things as the retention of soil profiles containing seeds, invertebrates and mycorrhizal fungi for re-use in areas of corridor or habitat creation or enhancement as opposed to the 'scorched earth' approach often taken in traditional building practices (van der Ree, 2004).

The creation of water 'stations' for bandicoots, and other wildlife, perhaps by the diverting of stormwater should be included in all new land releases, developments and surrounding bushland given the likelihood of ongoing drought and rising temperatures. The retention of a proportion of any trees felled in clearing works should be retained intact, as opposed to mulched, for later use in on-ground habitat creation. Local government agencies should develop programs and incentives to encourage other land managers and residents to do the same on private lands.

Newly released lands or developments should be cat-free or require cats to be curfewed at night for the protection of long-nosed bandicoots (and other wildlife) and bushland remnants or islands around new developments should be declared as Wildlife Protection Areas to ensure cats are not free to roam these areas. Simultaneously, the Companion Animals Act 1998 requires strengthening to facilitate the process of enforcement by council officers against roaming, nuisance or feral cats.

Upgraded or new roads should contain a number of fauna overpasses, underpasses and wildlife fencing to guide animals such as bandicoots towards these safe crossing points . These structures require ongoing monitoring of their use by bandicoots to enable future improvement and roadkill hotspots identified so their impacts can be mitigated.

At a local level, councils require further resourcing to ensure development application conditions relating to wildlife and native vegetation are met and where they fall short, these agencies are suitably positioned to administer adequate enforcement.

Ultimately, the use of the precautionary principle, one of the initial pillars of ecological sustainable development, needs to be resurrected to prevent the long-nosed bandicoots ‘death by a thousand cuts’ or ‘tragedy of the commons’ scenario particularly under the environmental uncertainty of intensifying climate change.

Finally, a number of the prescribed actions in the state and national Southern Brown Bandicoot Recovery Plans (2006 and 2010 respectively) appear equally as applicable for the long-nosed bandicoot in the urban matrix and should be implemented now *before* this species becomes so rare that more urban populations become fragmented and require listing as threatened.

The Greater Sydney Commission’s plan for the further urbanisation of Sydney is ambitious – it is hoped as much effort and resource will be spent ensuring the long-nosed bandicoot and other biodiversity is protected, maintained or enhanced as part of these development plans.

SUPPLEMENTARY MATERIAL

Appendix 1– Summary of bandicoot sighting records pre and post-cleaning, data sources, relevant metadata and limitations

Data Source	Source of Records	No. Records Exported in Download	Date Range of Records (pre-cleaning)	No. Records Removed due to Different or Unidentified species	No. Records Removed due to Invalid or Unverifiable Dates	No. Records Removed due to Location Accuracy	No. Records Removed due to Duplication	Final No. Records Post Cleaning	Date Range of Records (post-cleaning)
Atlas of Living Australia	Systematic Survey data collections; Royal Botanic Gardens herbarium database; OEH and national parks and Wildlife officers; Research scientists, ecological consultants, local government authorities and others as part of scientific licensing requirements; Australian museum; Universities; Zoological Boards; Forests NSW; Australian Bird and Bat Banding Scheme; Historical rpts / general public	9,764	12 Dec 1912 - 14 Sep 2018	79	54	67	9,488 (including Bionet)	142 (134 long-nosed and 8 southern brown)	12 Dec 1912 - 14 Sep 2018

Data Source	Source of Records	No. Records Exported in Download	Date Range of Records (pre-cleaning)	No. Records Removed due to Different or Unidentified species	No. Records Removed due to Invalid or Unverifiable Dates	No. Records Removed due to Location Accuracy	No. Records Removed due to Duplication	Final No. Records Post Cleaning	Date Range of Records (post-cleaning)
Bionet	Systematic Survey data collections; Royal Botanic Gardens herbarium database; OEH and national parks and Wildlife staff; Research scientists, ecological consultants, local government authorities and others as part of scientific licensing requirements; Australian museum; Universities; Zoological Boards; Forests NSW; Australian Bird and Bat Banding Scheme; Historical reports and the general public; *OEH Fox Threat Abatement Program (Fox TAP); **WildCount.	11,087	04 Sep 1967 – 04 Oct 2018	83	0	71	8,821	2,107 (1,888 long-nosed and 218 southern brown)	07 Sep 1967 – 23 Apr 2018

Data Source	Source of Records	No. Records Exported in Download	Date Range of Records (pre-cleaning)	No. Records Removed due to Different or Unidentified species	No. Records Removed due to Invalid or Unverifiable Dates	No. Records Removed due to Location Accuracy	No. Records Removed due to Duplication	Final No. Records Post Cleaning	Date Range of Records (post-cleaning)
Canada Bay Council	Council Officers; Ecological Consultants; General Public	3	1992, 1994- 08 May 2018	0	0	0	0	3	1992, 1994, 08 May 2018
Ku ring gai Council	Council Officers; Ecological Consultants; General Public.	2	05 May 2018	0	0	0	0	2	05 May 2018
Mosman Council	Council Officers; Ecological Consultants; General Public	2	2016	0	0	0	0	2	2016
Pittwater Council	Council Officers; Ecological Consultants; General Public	26	21 Aug 18 – 28 Sep 2018	0	0	0	0	26	21 Aug 18 – 28 Sep 2018
Willoughby Council	Council Officers; Ecological Consultants; General Public	1	2000	0	0	0	0	1	2016
Former Manly Council Roadkill Records	Council Officers; General Public	8	13 Feb 2013 - 15 May 2018	0	0	0	0	8	13 May 2013 - 15 May 2018

Data Source	Source of Records	No. Records Exported in Download	Date Range of Records (pre-cleaning)	No. Records Removed due to Different or Unidentified species	No. Records Removed due to Invalid or Unverifiable Dates	No. Records Removed due to Location Accuracy	No. Records Removed due to Duplication	Final No. Records Post Cleaning	Date Range of Records (post-cleaning)
Former Pittwater Roadkill Records	Council Officers; General Public	46	24 Aug 2000 – 17 May 2018	0	0	0	0	46	24 Aug 2000 – 17 May 2018
Sydney Wildlife	General Public; Veterinary Surgeons; Wildlife Rescue Volunteers	785	08 Jul 2013 – 29 Sep 2017	0	0	0	0	524	08 Jul 2013 – 29 Sep 2017
Research records	Research Scientists; Universities; Ecological Consultants	5	2016-2018	0	0	0	0	5	2016-2018

**FoxTAP refers to the NSW Fox Threat Abatement Plan 2010 and assists in the annual control of red foxes (Vulpes vulpes) a listed Key Threatening Process to many species of native biodiversity in NSW. This is an ongoing camera monitoring program that measures the responses of both foxes and threatened species over 50 sites and more than one million hectares of public and privately managed lands across NSW (OEH, 2010).*

***WildCount is an annual fauna monitoring program that commenced in 2012 using digital cameras situated in 200 sites across 146 parks and reserves in eastern NSW (OEH, 2018) also used to monitor the presence of threatened, native and exotic fauna.*

Appendix 2 - Summary Information of Demographic and Land Use Datasets and Layers used for Geospatial Analyses

Predictor Variable	Name of Dataset / Layer	Date of Creation / Last Revision	Source	Metadata Comments / Limitations	URL
Land Use Categories	Australian Land Use and Management (ALUM) Classification Version 7, Sydney Map Sheet 2012	Revised 2013	Office of Environment and Heritage Sharing and Enabling Environmental Data (SEED)	*Detailed urban mapping (1:10,000 scale) trial using high resolution Digital aerial imagery - Existing Land use information (circa 2003) has been used for non-rural zoned areas. This component of the 2013 land use has a reliability scale of 1:25,000. The areas where the circa 2003 land use product used include; urban, industrial, commercial and environmental local government LEP (Local Environment Planning) zones. It also includes areas of metropolitan Sydney that are excluded from the LLS Act 2016. Land use information has been captured in accordance with standards set by the Australian Collaborative Land Use Mapping Program (ACLUMP) and using the Australian Land Use and Management ALUM Classification. The ALUM classification is based upon the modified Baxter & Russell classification and presented according to the specifications contained in. For areas where circa 2003 land use information has been used the reliability scale is 1:25,000. This is identified in the source scale attribute for each feature in the dataset* (OEH, 2017).	http://www.agriculture.gov.au/abares/aclump/land-use/alumclassification

Predictor Variable	Name of Dataset / Layer	Date of Creation / Last Revision	Source	Metadata Comments / Limitations	URL
Population	Australian Population Grid 2006 and 2011	2006 and 2011	Australian Bureau of Statistics	http://www.abs.gov.au/websitedbs/censushome.nsf/home/dataquality?opendocument	http://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/1270.0.55.007Main+Features12011?OpenDocument
Housing	2006 and 2011 Census Community Profiles – Greater Sydney – Basic Community Profiles	2006 and 2011	Australian Bureau of Statistics	http://www.abs.gov.au/websitedbs/censushome.nsf/home/dataquality?opendocument	http://quickstats.censusdata.abs.gov.au/census_services/getproduct/census/2011/communityprofile/1GSYD?opendocument http://quickstats.censusdata.abs.gov.au/census_services/getproduct/census/2006/communityprofile/105?opendocument
Car Ownership	NSW Vehicle Registrations	26 May 2013	NSW Government Data -Roads and Maritime Services	*None Listed*.	https://data.nsw.gov.au/data/dataset/nsw-vehicle-registrations/resource/11f03ea7-83c1-4d8d-bc7d-7b9f5effa082
Road Density	NSW Road Dataset	10 Sept 2015	NSW Spatial Services	https://sdi.nsw.gov.au/catalog/search/resource/details.page?uuid=%7B10377F94-15B6-4F6D-8608-FEBCC59E373D%7D	https://sdi.nsw.gov.au/catalog/search/resource/details.page?uuid=%7B10377F94-15B6-4F6D-8608-FEBCC59E373D%7D

Appendix 3 -– Australian Land Use and Management (ALUM) Classification Version (8) 2016

1 Conservation and Natural Environments

1.1.0	Nature conservation
1.1.1	Strict nature reserves
1.1.2	Wilderness area
1.1.3	National park
1.1.4	Natural feature protection
1.1.5	Habitat/species mgmt area
1.1.6	Protected landscape
1.1.7	Other conserved area

1.2.0	Managed resource protectn
1.2.1	Biodiversity
1.2.2	Surface water supply
1.2.3	Groundwater
1.2.4	Landscape
1.2.5	Traditional indigenous uses

1.3.0	Other minimal use
1.3.1	Defence land - natural areas
1.3.2	Stock route
1.3.3	Residual native cover
1.3.4	Rehabilitation

2 Production Relatively Natural Environments

2.1.0	Grazing native vegetation

2.2.0	Production native forests
2.2.1	Wood production forestry
2.2.2	Other forest production

Minimum level of attribution

3 Production from Dryland Agriculture and Plantations

3.1.0	Plantation forests
3.1.1	Hardwood plantation forestry
3.1.2	Softwood plantation forestry
3.1.3	Other forest plantation
3.1.4	Environmental forest plantation

3.2.0	Grazing modified pastures
3.2.1	Native/exotic pasture mosaic
3.2.2	Woody fodder plants
3.2.3	Pasture legumes
3.2.4	Pasture legume/grass mixtures
3.2.5	Sown grasses

3.3.0	Cropping
3.3.1	Cereals
3.3.2	Beverage and spice crops
3.3.3	Hay and silage
3.3.4	Oilseeds
3.3.5	Sugar
3.3.6	Cotton
3.3.7	Alkaloid poppies
3.3.8	Pulses

3.4.0	Perennial horticulture
3.4.1	Tree fruits
3.4.2	Olives
3.4.3	Tree nuts
3.4.4	Vine fruits
3.4.5	Shrub berries and fruits
3.4.6	Perennial flowers and bulbs
3.4.7	Perennial vegetables and herbs
3.4.8	Citrus
3.4.9	Grapes

3.5.0	Seasonal horticulture
3.5.1	Seasonal fruits
3.5.2	Seasonal flowers and bulbs
3.5.3	Seasonal vegetables and herbs

3.6.0	Land in transition
3.6.1	Degraded land
3.6.2	Abandoned land
3.6.3	Land under rehabilitation
3.6.4	No defined use
3.6.5	Abandoned perennial horticulture

4 Production from Irrigated Agriculture and Plantations

4.1.0	Irrigated plantation forests
4.1.1	Irrigated hardwood plantation forestry
4.1.2	Irrigated softwood plantation forestry
4.1.3	Irrigated other forest plantation
4.1.4	Irrigated environmental forest plantation

4.2.0	Grazing irrigated modified pastures
4.2.1	Irrigated woody fodder plants
4.2.2	Irrigated pasture legumes
4.2.3	Irrigated legume/grass mixtures
4.2.4	Irrigated sown grasses

4.3.0	Irrigated cropping
4.3.1	Irrigated cereals
4.3.2	Irrigated beverage and spice crops
4.3.3	Irrigated hay and silage
4.3.4	Irrigated oilseeds
4.3.5	Irrigated sugar
4.3.6	Irrigated cotton
4.3.7	Irrigated alkaloid poppies
4.3.8	Irrigated pulses
4.3.9	Irrigated rice

4.4.0	Irrigated perennial horticulture
4.4.1	Irrigated tree fruits
4.4.2	Irrigated olives
4.4.3	Irrigated tree nuts
4.4.4	Irrigated vine fruits
4.4.5	Irrigated shrub berries and fruits
4.4.6	Irrigated perennial flowers and bulbs
4.4.7	Irrigated perennial vegetables & herbs
4.4.8	Irrigated citrus
4.4.9	Irrigated grapes

4.5.0	Irrigated seasonal horticulture
4.5.1	Irrigated seasonal fruits
4.5.2	Irrigated seasonal flowers and bulbs
4.5.3	Irrigated seasonal vegetables and herbs
4.5.4	Irrigated turf farming

4.6.0	Irrigated land in transition
4.6.1	Degraded irrigated land
4.6.2	Abandoned irrigated land
4.6.3	Irrigated land under rehabilitation
4.6.4	No defined use - irrigation
4.6.5	Abandoned irrigated perennial hort.

5 Intensive Uses

5.1.0	Intensive horticulture
5.1.1	Production nurseries
5.1.2	Shadehouses
5.1.3	Glasshouses
5.1.4	Glasshouses - hydroponic
5.1.5	Abandoned intensive horticulture

5.2.0	Intensive animal production
5.2.1	Dairy sheds and yards
5.2.2	Feedlots
5.2.3	Poultry farms
5.2.4	Piggeries
5.2.5	Aquaculture
5.2.6	Horse studs
5.2.7	Saleyards/stockyards
5.2.8	Abandoned intensive animal production

5.3.0	Manufacturing and industrial
5.3.1	General purpose factory
5.3.2	Food processing factory
5.3.3	Major industrial complex
5.3.4	Bulk grain storage
5.3.5	Abattoirs
5.3.6	Oil refinery
5.3.7	Sawmill
5.3.8	Abandoned manufacturing and industrial

5.4.0	Residential and farm infrastructure
5.4.1	Urban residential
5.4.2	Rural residential with agriculture
5.4.3	Rural residential without agriculture
5.4.4	Remote communities
5.4.5	Farm buildings/infrastructure

5.5.0	Services
5.5.1	Commercial services
5.5.2	Public services
5.5.3	Recreation and culture
5.5.4	Defence facilities - urban
5.5.5	Research facilities

5.6.0	Utilities
5.6.1	Fuel powered electricity generation
5.6.2	Hydro electricity generation
5.6.3	Wind electricity generation
5.6.4	Solar electricity generation
5.6.5	Electricity substations and transmission
5.6.6	Gas treatment, storage and transmission
5.6.7	Water extraction and transmission

5.7.0	Transport and communication
5.7.1	Airports/aerodromes
5.7.2	Roads
5.7.3	Railways
5.7.4	Ports and water transport
5.7.5	Navigation and communication

5 Intensive Uses continued

5.8.0	Mining
5.8.1	Mines
5.8.2	Quarries
5.8.3	Tailings
5.8.4	Extractive Industry not in use

5.9.0	Waste treatment and disposal
5.9.1	Effluent pond
5.9.2	Landfill
5.9.3	Solid garbage
5.9.4	Incinerators
5.9.5	Sewage/sewerage

6 Water

6.1.0	Lake
6.1.1	Lake - conservation
6.1.2	Lake - production
6.1.3	Lake - intensive use
6.1.4	Lake - saline

6.2.0	Reservoir/dam
6.2.1	Reservoir
6.2.2	Water storage - intensive use/farm dams
6.2.3	Evaporation basin

6.3.0	River
6.3.1	River - conservation
6.3.2	River - production
6.3.3	River - intensive use

6.4.0	Channel/aqueduct
6.4.1	Supply channel/aqueduct
6.4.2	Drainage channel/aqueduct
6.4.3	Stormwater

6.5.0	Marsh/wetland
6.5.1	Marsh/wetland - conservation
6.5.2	Marsh/wetland - production
6.5.3	Marsh/wetland - intensive use
6.5.4	Marsh/wetland - saline

6.6.0	Estuary/coastal waters
6.6.1	Estuary/coastal waters - conservation
6.6.2	Estuary/coastal waters - production
6.6.3	Estuary/coastal waters - intensive use

New South Wales Office of Environment and Heritage, 2017,
Sharing and Enabling Environmental Data (SEED), Land Use 2013.
https://datasets.seed.nsw.gov.au/dataset/nsw-landuse-2013

Appendix 4 - Summary of ALUM Land Use Classifications (2012) and Reclassifications undertaken for mapping analysis in this study

Classifications included in this Study	Original Class in ALUM (2012)	Original ALUM (2012) Land use sub-classes re-classified	Reason for re-classification
(i) National park	(1) Conservation and Natural Environments	All sub-classes in this ALUM classification included in national park classification in this study.	N/A
	(2) Production from Relatively Natural Environments	All sub-classes in this ALUM classification included national park classification in this study.	Land use described in ALUM as relatively natural environment and consists of grazing native vegetation, production native forests (wood production forest and other forest production).
(ii) Agricultural and Rural	(3) Production from Dryland Agriculture and Plantations	All sub-classes in this ALUM classification included in Agricultural and Rural land classification in this study.	N/A
	(4) Production from Irrigated Agriculture and Plantations	All sub-classes in this ALUM classification included in Agricultural and Rural land classification in this study.	N/A
(iii) Urban and Residential	(5) Intensive Uses	5.4.0 Residential and Farm Infrastructure 5.4.1 Urban residential 5.4.2 Rural residential with agriculture 5.4.3 Rural residential without agriculture 5.4.4 Remote communities 5.4.5 Farm buildings / infrastructure	More appropriate for these sub-categories to be reclassified as Urban and Residential land for the purpose of this study as bandicoots are known to be present in areas where this type of development occurs.
(iv) Industrial and Commercial	(5) Intensive Uses	Section 5.4.0 Residential and Farm Infrastructure and sub-categories removed from this ALUM classification (see above). All other land uses in this classification retained as Industrial and Commercial in this study.	As above.
(v) Water	(6) Water	All sub-classes in this ALUM classification included in Water classification in this study	N/A

Appendix 5 – Southern brown bandicoot presence per km^2 grid cell per LGA between 01 September 1993 and September 30 2018

Local Government Area (LGA)pre-2016 Council amalgamations	Total LGA Area (km^2)	Total No. Grid cells (km^2) containing southern brown bandicoots (01-Sep-1993-31-Aug-2018)	Southern brown bandicoot density per LGA
Hornsby	462.09	1	0.0021
Ku ring gai	85.39	2	0.0234
Pittwater	90.31	3	0.0332
Warringah	149.33	13	0.0870
Wollondilly	2557.41	2	0.0011
TOTAL		**21**	

Appendix 5 – Ethics Approval

From: Faculty of Science Research Office <sci.ethics@mq.edu.au>
Sent: Thursday, 22 February 2018 3:58 PM
To: Michelle Leishman; Alexandra Carthey; sonja.elwood@students.mq.edu.au
Cc: fse.ethics; Katherine Shevelev; Cathi Humphrey-Hood
Subject: Ethics application 5201800111 Leishman - Final Approval

Dear Prof Leishman

RE: Ethics project entitled: "History and Ecology of Sydneys Urban Bandicoots"
Ref number: 52012800111

The Faculty of Science and Engineering Human Research Ethics Sub-Committee has reviewed your application and granted a Conditional approval, 22/02/2018:

Condition: Please change the start date of the project - now 1/01/2018.
Once the start date is amended, you will be able to commence your research.

This research meets the requirements of the National Statement on Ethical Conduct in Human Research (2007). The National Statement is available at the following web site:

http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/e72.pdf.

The following personnel are authorised to conduct this research:

Prof Michelle Leishman
Dr Alexandra Ralph
Ms Sonja Elwood

NB. STUDENTS: IT IS YOUR RESPONSIBILITY TO KEEP A COPY OF THIS APPROVAL EMAIL TO SUBMIT WITH YOUR THESIS.

Please note the following standard requirements of approval:

1. The approval of this project is conditional upon your continuing compliance with the National Statement on Ethical Conduct in Human Research (2007).

2. Approval will be for a period of five (5) years subject to the provision of annual reports.

Progress Report 1 Due: 22/02/2019
Progress Report 2 Due: 22/02/2020
Progress Report 3 Due: 22/02/2021
Progress Report 4 Due: 22/02/2022
Final Report Due: 22/02/2023

NB. If you complete the work earlier than you had planned you must submit a Final Report as soon as the work is completed. If the project has been discontinued or not commenced for any reason, you are also required to submit a Final Report for the project.

Progress reports and Final Reports are available at the following website:

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics/forms

3. If the project has run for more than five (5) years you cannot renew approval for the project. You will need to complete and submit a Final Report and submit a new application for the project. (The five year limit on renewal of approvals allows the Committee to fully re-review research in an environment where legislation, guidelines and requirements are continually changing, for example, new child protection and privacy laws).

4. All amendments to the project must be reviewed and approved by the Committee before implementation. Please complete and submit a Request for Amendment Form available at the following website:

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics/forms

5. Please notify the Committee immediately in the event of any adverse effects on participants or of any unforeseen events that affect the continued ethical acceptability of the project.

6. At all times you are responsible for the ethical conduct of your research in accordance with the guidelines established by the University. This information is available at the following websites:
http://www.mq.edu.au/policy/

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics/policy

If you will be applying for or have applied for internal or external funding for the above project it is your responsibility to provide the Macquarie University's Research Grants Management Assistant with a copy of this email as soon as possible. Internal and External funding agencies will not be informed that you have final approval for your project and funds will not be released until the Research Grants Management Assistant has received a copy of this email.

If you need to provide a hard copy letter of Final Approval to an external organisation as evidence that you have Final Approval, please do not hesitate to contact the Ethics Secretariat at the address below.

Please retain a copy of this email as this is your official notification of final ethics approval.

Yours sincerely,
Human Research Ethics Sub-Committee
Faculty of Science and Engineering
Macquarie University
NSW 2109

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