Faculty of Science, Medicine & Health - Honours Theses

University of Wollongong Thesis Collections

2018

Scoping for potential wildlife crossings for koalas and marsupial gliders in the Sutherland Shire and Campbelltown regions of New South Wales, Australia

D Karas

Follow this and additional works at: https://ro.uow.edu.au/thsci

Recommended Citation

Scoping for potential wildlife crossings for koalas and marsupial gliders in the Sutherland Shire and Campbelltown regions of New South Wales, Australia

Abstract

Arboreal, or "tree-dwelling", species such as koalas and marsupial gliders may potentially be more vulnerable to the effects of roads, habitat loss and habitat fragmentation due to their high specialisation. The emerging concept of road ecology attempts to reduce the effects of animals on roads and identifies wildlife mitigation structures, including wildlife crossings and exclusion fencing, as the best methods to combat the issue of habitat fragmentation. The Sutherland Shire and Campbelltown regions of Sydney, Australia are of particular interest due to the populations of koalas and various glider species. These regions also have several major roadways present that can impact on species movement and have the potential to disrupt population dynamics and reduce population numbers from animal-vehicle collisions. Crossing structures and other mitigation measures have been used extensively in Australia and worldwide with various levels of success.

Spatial analysis of New South Wales BioNet Atlas data was undertaken using GIS software to find areas of high species presence, or "hotspots". Within the koala dataset, several hotspots were found which mainly existed along the forested and cleared land edge of Campbelltown that is separated by roads. An area of concern was found on a 3.8km segment of Appin Road whereby 12 koalas roadkills were on record, 10 of which coincided with the previous hotspot analysis. Within the marsupial gliders dataset, two main hotspots of species presence were identified. A basic cost surface was also created to generate a suitability and traversability index within the study area. While both of these methods were effective, some issues with data biases and areas with incomplete data were present. Overall, a range of criteria needs to be utilised in order to effectively determine if a mitigation structure is required at a specific location. It is recommended that this study be used as a foundation for future research.

Degree Type
Thesis

Degree Name
BEnviSci Hons

Department
School of Earth & Environmental Sciences

Advisor(s)
Laurie Chisholm

Keywords
Arboreal, koalas and marsupial gliders, road crossing

Scoping for potential wildlife crossings for koalas and marsupial gliders in the Sutherland Shire and Campbelltown regions of New South Wales, Australia

By

Dean Karas

A research report submitted in partial fulfilment of the requirements for the award of the degree of

BACHELOR OF ENVIRONMENTAL SCIENCE (HONOURS)

School of Earth and Environmental Sciences
Faculty of Science, Medicine and Health
The University of Wollongong

October 2018

The information in this thesis is entirely the result of investigations conducted by the author, unless otherwise acknowledged, and has not been submitted in part, or otherwise, for any other degree of qualification.

Name: Dean Karas

Signature:

Date: 23/10/2018

Acknowledgements

Firstly, I would like to thank my supervisors, Laurie Chisholm and Beth Noel, for their contribution to this paper. Their knowledge, ideas and support throughout the year have been invaluable.

I would also like to thank Heidi Brown for her ideas around the spatial analysis aspect of this study, as well as providing data for this research.

On behalf of every student undertaking honours this year, I would like to thank Marina for her encouragement and support throughout the year and for also for providing quality sandwiches at meetings.

Lastly, I would like to thank my parents, peers and dogs for keeping me sane throughout the duration of writing this thesis.

Abstract

Arboreal, or "tree-dwelling", species such as koalas and marsupial gliders may potentially be more vulnerable to the effects of roads, habitat loss and habitat fragmentation due to their high specialisation. The emerging concept of road ecology attempts to reduce the effects of animals on roads and identifies wildlife mitigation structures, including wildlife crossings and exclusion fencing, as the best methods to combat the issue of habitat fragmentation. The Sutherland Shire and Campbelltown regions of Sydney, Australia are of particular interest due to the populations of koalas and various glider species. These regions also have several major roadways present that can impact on species movement and have the potential to disrupt population dynamics and reduce population numbers from animal-vehicle collisions. Crossing structures and other mitigation measures have been used extensively in Australia and worldwide with various levels of success.

Spatial analysis of New South Wales BioNet Atlas data was undertaken using GIS software to find areas of high species presence, or "hotspots". Within the koala dataset, several hotspots were found which mainly existed along the forested and cleared land edge of Campbelltown that is separated by roads. An area of concern was found on a 3.8km segment of Appin Road whereby 12 koalas roadkills were on record, 10 of which coincided with the previous hotspot analysis. Within the marsupial gliders dataset, two main hotspots of species presence were identified. A basic cost surface was also created to generate a suitability and traversability index within the study area. While both of these methods were effective, some issues with data biases and areas with incomplete data were present. Overall, a range of criteria needs to be utilised in order to effectively determine if a mitigation structure is required at a specific location. It is recommended that this study be used as a foundation for future research.

Table of Contents

List of Figures

List of Tables

1. Introduction

Roads are a common feature amongst almost every landscape. The planning, creation and subsequent upgrades to these roads is described as being "pervasive" to landscapes (Bennett, 1991; Ramp et al., 2006; van der Ree et al., 2008; Jones et al., 2011), causing a range of problems to the surrounding habitat and animals alike. Remnants of the natural environment increasingly occur as a mosaic of large and small patches – survivors of environments that have been carved up to develop new forms of productive land use for humans (Bennett, 1999). In essence, roads are a physical paradox in that they connect pieces of land together for society, yet the same road system slices nature into pieces (Forman et al., 2003). Roads are highly beneficial for humans, allowing the travel of humans, goods and services. For animals and the environment, however, roads are disruptive to natural processes.

1.1 Habitat fragmentation, habitat loss and the presence of species on roads

Of primary concern within a species conservation context is how roads cause habitat fragmentation and the subsequent problems that may arise from this. Habitat fragmentation (*Figure 1*) is the term used to describe the changes that occur when large blocks of vegetation are incompletely cleared, leaving multiple smaller blocks that are separated from each other (Bennett, 1999; Fahrig, 2003). Habitat fragmentation is a dynamic process that results in marked changes to habitat patterns in a landscape over time and involves three key concepts: the loss of habitat, a reduction of patch or remnant size and an increasing distance between patches (Andrén, 1994; Bennett, 1999; Fahrig, 2003). One such consequence of habitat fragmentation is the creation of edge effects. An edge effect is the result of a disturbance causing two contrasting habitats to suddenly converge without any natural gradient (Andrews, 1990) – often the case for remnant habitat patches and the external matrix. Species living in these remnant habitat patches may become confined to smaller areas within the interior habitat of remnant patch (Queensland Government, 2000).

Habitat loss and habitat fragmentation are identified as the leading cause of biodiversity loss worldwide and there is now a major challenge that exists to maintain and conserve biodiversity in landscapes dominated by human land use (Bennett, 1999).
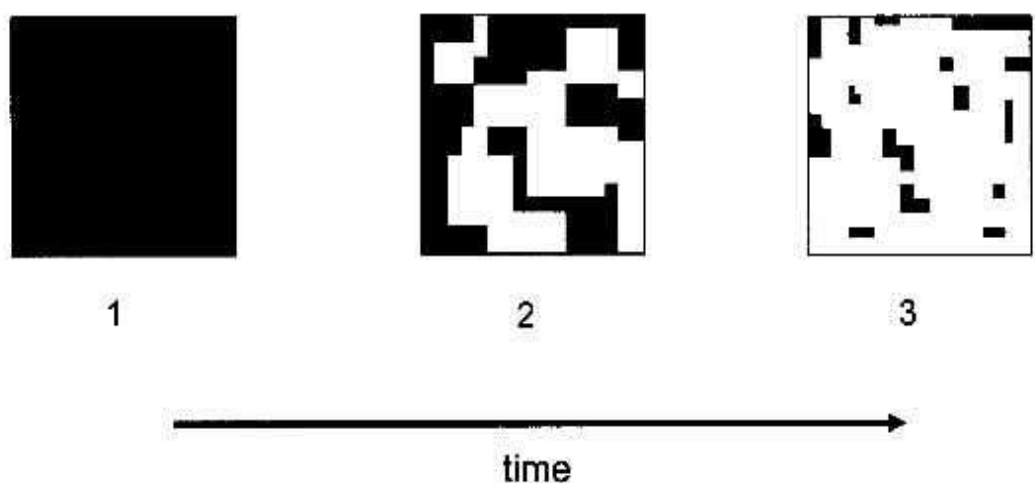
Figure 1: The habitat fragmentation process. 1 represents a large, unfragmented habitat; 2 represents the fragmentation of the habitat into smaller patches; and 3 represents isolated patches in which the habitat matrix becomes dominant. Image from Fahrig (2003).

The consequences of habitat fragmentation are significant and the effect of roads on these fragmented habitats is major. Roads may present a partial or complete barrier to the movement of animals between habitat patches, which is known as the 'road barrier effect' (Goldingay & Whelan, 1997; Forman et al., 2003; Taylor & Goldingay, 2004; Jones et al., 2011). The result of the road barrier effect tends to create subpopulations of species whereby roads divide large, once continuous populations into small and partially isolated local populations (Forman & Alexander, 1998; Taylor & Goldingay, 2003). Fragmentation effects occur at a rate at which an animals ability to traverse the developed area is reduced (van der Ree et al., 2008). When—or if—movement is halted by this break in habitat, the road infrastructure becomes a complete barrier to animal movement (van der Ree et al., 2008; Jones et al., 2011). The extent to which populations become functionally isolated depends on the availability of habitat corridors, composition of the landscape matrix and the ability of a species to move freely through the environment (Taylor et al., 2011; Goldingay et al., 2013).

1.2 Wildlife-vehicle collisions

Animals may be forced onto roads when attempting to move between habitat patches as part of their daily movements within their home range. As such, wildlife-vehicle collisions become extremely common, posing a threat to both wildlife and humans

(*Figure 2*). Wildlife-vehicle collisions, also called animal-vehicle collisions within the literature, are the result of animals being present on roadways, causing a harmful—and often fatal—collision between an animal and a vehicle (Andrews, 1990; Rowden et al., 2008). These collisions are harmful to both the animal population, due to the possibility of animal loss disrupting population dynamics, and to occupants of vehicles who may be significantly injured after directly hitting or swerving to avoid an animal. In a review paper by Rowden et al. (2008), collation of data from road crash reporting databases found that in New South Wales between 2001 to 2005 there were 11 fatal crashes, 1,399 injury-causing crashes and 2,532 non-casualty crashes attributed to swerving to avoid an animal. Similarly, in crashes where an animal was the first object hit, there were 14 fatal crashes, 716 injury-causing crashes and 1,751 non-casualty crashes over the same period.

Figure 2: An image of a deceased koala struck by a vehicle on Heathcote Road, Holsworthy. Image from Beth Noel (Sutherland Shire Council)

According to Ramp et al. (2006), three sets of factors are likely to determine collisions between vehicles and wildlife:

- The first set of factors is the likelihood of the animal to be present on the road, which is determined by several spatial factors, such as home range, proximity to resources, and breeding and dispersal effects.
- The second set of factors relates to the likelihood of a vehicle being present, which can be quantified by traffic statistics.

- The third set of factors is the presence of road and human features, including vehicle speed, road curvature, driver visibility, time of day and the tiredness of the driver.

1.3 Road ecology and habitat corridors

Recently, there has been an emergence in attempting to protect species that live near roadways. This relatively new concept, termed 'road ecology', attempts to quantify the negative relationship between the natural environment, the road system and animal species (Forman et al., 2003), with the aim of avoiding, minimising, mitigating or offsetting impacts (Rytwinski et al., 2015). As the name suggests, road ecology entails the combinations of the terms 'road' and 'ecology' – roads being an open way for the passage of vehicles and ecology being the study of interactions between organisms and the environment. Therefore, the combination of these terms describes the essence of road ecology; that is, the interaction of organisms and the environment linked to roads and vehicles (Forman et al., 2003).

One of the most significant aspects of road ecology is to maintain the natural habitat corridors that animals use to travel. Habitat corridors, also referred to as "green" corridors, are links between habitats. These links may be provided by roadsides, private bushland, gardens, farmland or any other linear strips of vegetation that offers a continuous, or near continuous, pathway between two habitats that are otherwise separated by an inhospitable habitat matrix (Bennett, 1999). Habitat corridors are a part of the concept of connectivity, which is used to describe how the spatial arrangement of the landscape affects movements of organisms amongst habitat patches (Bennett, 1999). Land managers and scientists are increasingly incorporating habitat connectivity into designs of reserves and landscapes, recognising that connected habitat patches are likely to be more successful at supporting viable wildlife populations than isolated patches (Siitonen et al., 2002; Carly et al., 2013).

While roads are predominantly seen as a barrier to species movement, they can also serve as corridors for movement. Roads include the road surface, its maintained roadside edges and any vegetated strips running parallel to the road surface (Forman &

Alexander, 1998; Forman et al., 2003). As habitat fragmentation and loss are more apparent at larger scales, much of the natural vegetation running along roadsides is lost during and in post-construction maintenance activities, which may occur as the result of incremental losses in what is an already vulnerable habitat (van der Ree et al., 2008). Due to road design, vegetation running parallel to roads can receive a significant amount of water following rainfall. While animals may be drawn to this evergreen roadside vegetation, another reason for animals being present in these areas is due to the pooling of water in roadside ditches, drains or streams (Forman & Alexander, 1998; Magnus et al., 2004), which would be significant during times of low rainfall or drought when water availability in waterways is scarce.

1.4 Species response to habitat fragmentation

Species respond to habitat fragmentation and habitat loss in different ways. One of the most affected features of a species is a marked change in species dynamics (Bennett, 1991), which involves changes to interaction patterns such as breeding and foraging. Differences in the home range area, body size, food resources and foraging patterns, nesting and shelter requirements, as well as species sensitivity and tolerance to habitat disturbance all influence species-specific responses to fragmentation (Bennett, 1991; 1999). Animal species vary greatly in their level of habitat specialisation and their tolerance to habitat disturbance and change. These attributes are important influencers of how they perceive a particular landscape and the level of connectivity that it provides (Bennett, 1999).

Loss of habitat will decrease the viability of populations by reducing the area in which an animal can be supported (van der Ree et al., 2008). Division of habitat into smaller fragments results in lower population sizes – and when roads act as a partial or complete barrier to movement, these small populations may not be connected to other populations and hence are at a higher risk of extinction (van der Ree et al., 2008; Rhodes et al., 2008). When roads fragment populations by forming barriers to movement, animals will become isolated from resources and mates, and without species dispersal and movement, extinction will occur in habitat fragments that are too small to contain viable populations (Bolger et al., 1997).

1.5 Crossing structures

According to Polak et al. (2014), three main approaches can be taken regarding roadkill measures. The first is a "do nothing" approach whereby no action is taken on attempting to reduce or mitigate roadkill and other effects. The second approach is wildlife exclusion fencing around a roadway that attempts to prevent an animal from entering onto a road or filters them towards a desirable location. The third approach – and an approach that can be used in conjunction with the second approach – is the creation of a wildlife crossing structure, which is often identified as the optimal strategy to reduce wildlife roadkills. However, there are additional options not mentioned by Polak et al. (2014), such as signage, roadside sensors and programs to increase road user awareness that have also been utilised.

Figure 3: A rope-bridge (form of overpass) located at Karuah, NSW. Image from Goldingay et al., (2013)

Wildlife crossing structures, such as those pictured in *Figure 3*, are identified as one of the best mitigation methods to reduce wildlife roadkill, increase habitat connectivity and regenerate habitat corridors that may have otherwise been disrupted by roads and more general urbanisation (Mata et al., 2008; 2009). The first recognised use of crossing structures occurred in the 1960s in France, in which expanding road construction caused problems for French hunters and thus 150 "game bridges" were constructed for game animals to cross over highways (Forman et al., 2003). The next globally

recognised crossing structure was an overpass constructed in 1978/79 in southwest Utah to enhance deer migratory movement along a ridge (Forman et al., 2003).

Since the original implementation of crossing structures and the increasing awareness of the concept of road ecology, the use of crossing structures is much more common. The bridges constructed in 1960s France are most likely an inspiration for the later construction of wildlife overpasses, or "green bridges", in several nations (Forman et al., 2003). Mata et al. (2008) have shown that a broad range of species will use multiple different crossing structures to cross a road, but the extent to which species will trend towards certain structures, what makes these structures effective and how this varies between landscapes and species is relatively unknown.

The extensive road networks in Australia pose as a major threat to wildlife. The Bureau of Infrastructure, Transport and Regional Economics (2015) reported that there is over 873,000km of road in Australia of which over 207,000km is present in New South Wales. The presence of two major national parks – Heathcote National Park and the Royal National Park – as well as other nature complexes, such as Dharawal National Park, Georges River National Park and Garawarra reserve, means that animals are in close proximity to roads and at significant risk to the tens of thousands of vehicles travelling these roads each day.

Arboreal, or "tree-dwelling", mammals such as koalas and marsupial gliders are potentially more vulnerable to the discontinuous habitat created by roads (Taylor & Goldingay, 2009) due to their highly specialised requirements (Taylor & Goldingay, 2012; Dennison et al., 2016). Arboreal mammals live above the ground in the shrub or canopy tree layer and generally are dependent on networks of trees and shrubs to move through cleared land (Bennett, 1999). Thus, habitat fragmentation resulting from roads and more general urbanisation can cause havoc to these species.

1.6 Study objectives

The extensive road networks within the Sutherland Shire and Campbelltown local government areas pose a major threat to wildlife that is present in the surrounding habitats. By conducting a literature review into species life history traits, crossing structures in Australia, trends in international studies and identifying knowledge gaps when determining the "success" of a structure, the objective of the literature review is to determine the preferred crossing structures of koalas and marsupial gliders. Thereafter, simple spatial analysis techniques will be used to find potential areas of high species presence and areas where roads are acting as barriers to species movement within the study area, from which further research will be recommended.

1.7 Aims

The key aims of this study are:

1) To present the life history traits of koalas and marsupial gliders.

2) Outline the types of mitigation structures using Australia examples. Trends that are present in international literature will also be identified.

3) Critically access how the success of mitigation structures is determined and identify knowledge gaps.

4) Use simple spatial analysis techniques to identify hotspots of species presence, as well as determine areas that may be unsuitable or difficult to traverse.

5) Highlight criteria that should be used when assessing the potential of a crossing structure in an area.

6) Suggest strategies for potential future research.

2. Background and literature review

A sizeable amount of literature exists for this topic, which will be summarised and critically analysed with knowledge gaps within the literature being identified. The life history of the selected species, koalas and marsupial gliders, will be highlighted, which will provide insight into their behavioural trends. From there, different mitigation measures will be defined and Australian examples of structures or measures where the selected species have been observed will be discussed. International literature will then be analysed – and while international literature will not provide insight into the crossing structure usage of the chosen Australian species, some observable trends may become apparent. Thereafter, "success" of crossing structures – which is one of the most difficult aspects of a crossing structure to determine – will be critically analysed using existing literature, with particular emphasis on the inconsistencies of the term "success" within the literature being discussed.

2.1 Selected species

For effective mitigation of road effects, it is important to identify the species whose populations are reduced by roads so that mitigation efforts can be tailored to those species (Rytwinski & Fahrig, 2012). Broad-scale research into the behaviour of a particular species is required to identify where resources would best be deployed to evaluate areas for potential mitigation structures (Rowden et al., 2008). The species selected for this study are koalas and marsupial gliders. Both koalas and marsupial gliders are arboreal species, which are potentially at greater risk from the discontinuous habitat that is created by roads (Taylor & Goldingay, 2009). As arboreal mammals are specialist species, they are particularly vulnerable to the effects of habitat loss as they are limited in their choice of resources (Dennison et al., 2016).

Originally, Lindenmayer et al. (1999) found that the life history attributes of eight marsupial species provided no insight into fragmentation effects and landscape context. However, a more recent study by Rytwinski & Fahrig (2012) emphasized the importance of a species life history in relation to habitat fragmentation. It is now widely accepted that road-related mortality affects species differently depending on their life

history traits (Polak et al., 2014) and a particular species' response to habitat loss is also likely to vary spatially due to different landscape characteristics, such as habitat fragmentation, landscape history and land use (Rhodes et al., 2008).

2.1.1 Koalas

The koala (*Phascolarctos cinereus*) is an arboreal mammal endemic to eastern and southern Australia. Koalas are an Australian national icon, having significant intrinsic value in Australian society and major economic value for tourism. In a study by Hundloe & Hamilton (1997) koala tourism was valued at $1.8 billion, with this amount rising to $3.2 billion in 2014 (Conrad, 2014). Koalas are listed as 'Vulnerable' under the New South Wales Biodiversity Conservation Act 2016 (previously under the NSW Threatened Species Conservation Act 1995) and the Federal Environment Protection and Biodiversity Conservation Act for New South Wales, Queensland and the Australian Capital Territory. They are also listed as 'Threatened' by the New South Wales and Commonwealth government in 1992 and 2012. Koalas have several major threats, including habitat fragmentation and loss, vehicle strike, dog attacks, fire, disease, drought and heatwaves (NSW Chief Scientist and Engineer, 2016). It is estimated that there are approximately 36,000 koalas in New South Wales – a 26% decline over the past three koala generations, which represents between 15-21 years (Adams-Hosking et al., 2016).

Koalas are folivores, feeding on a selective diet of a subset of the Eucalyptus species (Dennison et al., 2016), but they are also known to consume foliage of related genera, including Corymbia, Angophora and Lophostemon species (NSW RMS, 2015). In total, koalas feed on primary food trees of approximately 70 eucalyptus species and 30 non-eucalypt species although each population or individual will usually limit themselves to very few primary food tree species (NSW Chief Scientist and Engineer, 2016). Koalas show a strong feeding preference between individual trees within a species and also use the same set of trees for social interaction outside of the breeding season (NSW RMS, 2015). The quality of life for a koala depends on a range of factors, including the species and size of the trees present, the structural diversity of vegetation, soil quality, climate and rainfall, and the size and previous disturbance of the habitat patch (Reed et al.,

1990, as cited in NSW RMS, 2015; DECC, 2008).

Koalas reside in a specific home range with this value varying between studies from 4ha (Goldingay & Dobner, 2014) to 22.7ha (Lassau et al., 2008), with male koalas having a greater home range than female koalas (Lassau et al., 2008). However, koalas have also been known to be active movers in remnants of up to 500ha (DECC, 2008). Although koalas are highly mobile on the ground they do not always need to descend onto the ground to change trees (Goldingay & Taylor, 2017). Where the habitat allows, koalas can traverse between trees using connecting branches or may even make short jumps to closely spaced trees. Koalas living in "poor" habitats, which are areas considered as being heavily fragmented or to have poor living conditions, will also have a greater home range due to the necessity to travel further for their requirements, as the availability of palatable trees largely dictates the home range of a koala (Lassau et al., 2008).

As well as this, studies have found that koalas show female-mediated genetic flow, suggestive of male-based dispersal (Fowler et al., 2000) and major roads have also been shown to act as a barrier to koala gene flow (Lee et al., 2009). In a study by Lassau et al. (2008), 123 koala deaths occurred between January 1992 and October 2006 on a 3.5km stretch of road in Bonville, NSW. The average age of these animals was four years, which hints at young, dispersing koalas attempting to cross the highway, whereas older—or "resident"—koalas recognised structural features as boundaries and made a behavioural decision to not cross a roadway. Similarly, a study by Dexter et al. (2017) confirmed this finding of younger male koalas dispersing, stating that koalas aged less than five years old were more likely to cross roads. With a koalas typical lifespan in the wild being between 10 and 15 years, the loss of these younger koalas may significantly alter species dynamics.

Koala breeding season occurs from September to January and it is expected that movements are more frequent and extensive during this time (NSW RMS, 2015). Koalas have been shown to use both overpasses (e.g. Dexter et al., 2017) and various underpasses (e.g Dexter et al., 2017; Goldingay et al., 2018); however, studies of koalas within underpasses have shown that they were only detected on the ground when moving through an underpass and did not use timber railings (also known as

"furniture") when travelling through this structure (Goldingay et al., 2018).

2.1.2 Marsupial gliders

Marsupial gliders, also referred to as gliding mammals, gliding marsupials, gliding possums or simply as 'gliders', are small nocturnal mammals that are endemic to the east coast of Australia between Victoria and Queensland. Being arboreal animals, marsupial gliders are highly specialised and rely on tree cover to move within and amongst their home range (Sharpe & Goldingay, 2007; Taylor & Goldingay, 2009). The size of a glider's home range is controlled by its diet and size-dependent metabolic needs (Sharpe & Goldingay, 2007), and gaps in tree cover greater than its gliding distance limits a marsupial gliders ability to move between habitat patches when foraging and dispersing (Taylor et al., 2011). While a large proportion of gliders remain in trees, many individuals spend a significant amount of time on the ground and show no reluctance to cross roads (Taylor & Goldingay, 2009). Glider populations have been known to be present in remnants as small as 10-20ha, but higher glider population densities were present in remnants between 200-1000ha (Rowston et al., 2002). Gliders require a hollow-bearing, floriferous eucalypt open forest or woodland with a Banksia or Acacia shrub layer that provides den sites in tree cavities and a good winter supply of nectar (NSW Scientific Committee, 2008).

Many glider species exist on the east coast on Australia, including sugar gliders (*Petaurus breviceps*), greater gliders (*Petauroides volans*), yellow-bellied gliders (*Petaurus australis*), squirrel gliders (*Petaurus norfolcensis*) and feathertail gliders (*Acrobates pygmaeus*). The habitat requirements for each species are relatively similar, with the major differences arising from body size and food preferences. Feathertail gliders are the smallest of the marsupial gliders weighing a maximum of 15g (Lindenmayer, 1997); sugar gliders have a maximum adult weight of 130g; squirrel gliders typically weight between 190 and 330g (NSW Scientific Committee, 2008); and the largest glider species, greater gliders, have an adult weight in excess of 1kg (Lindenmayer, 1997). Being omnivorous, the diet of a glider consists of arthopods, exudates, nectar, pollen, sap and gum (Smith, 1982; Sharpe & Goldingay, 2007). Squirrel gliders are also known to consume small birds and their eggs (Dobson et al., 2005), while greater gliders are folivores and mainly feed on the leaves of eucalypts

(Possingham et al., 1994). This diet will vary seasonally, consuming more exudates during autumn and winter while feeding on predominantly insects during spring and summer (Smith, 1982).

Not much is known about the behavioural and physical attributes of gliders, although some studies have quantified various aspects of gliders. One such study by Goldingay (2014) found that yellow-bellied gliders glide at an angle of 27^0 for between four to five seconds, travelling at an estimated horizontal speed of between 3.75 and 8.25 metres per second. Squirrel gliders have been found to be altitude limited to 300m (Rowston et al., 2002) and live in small family groups of between two and 10 individuals, usually consisting of two adult males, two adult females and their young (NSW Scientific Committee, 2008; Taylor & Goldingay, 2009).

2.2 Roadkill mitigation measures – crossing structures

Wildlife crossing structures are often identified as the best method to reduce the effects of habitat fragmentation. Defined as "a physical structure that increases the permeability of the road or other linear infrastructure by facilitating the safe passage of animals over or under it and in the case of roads and railways, preventing collision with vehicles", wildlife crossing structures attempt to reduce the numerous effects brought upon by habitat fragmentation (van der Ree et al., 2008, p. 8).

Roadkill mitigation measures can occur over various spatial scales. Magnus et al. (2004) identifies three spatial scales over which crossing structures can be deployed. The first spatial scale is in a "blackspot" or "hotspot" – an area of high animal population density, an area where animal-vehicle collisions are frequent or a location where an animal frequently travels in its home range. The second spatial scale is along a stretch of road or several segments of habitat along a road where many species are killed (Bennett, 1991). The final spatial scale in which crossing structures can be installed is over a whole region or even statewide mitigation, which often results from the need to protect a vulnerable species for greater environmental or economic reasons. Both koalas and certain species of marsupial gliders could be considered as species worthy of statewide

mitigation: koalas due to their economic and intrinsic value to Australian society and marsupial gliders because of their status on state protection legislation.

In an Australia review paper by van der Ree et al. (2008) for the Department of Environment and Heritage, several key wildlife crossing structures that may be used to mitigate habitat fragmentation are identified. These structures are generally classified under two groups:

- Overpasses, which consist of land bridges, glider poles and canopy bridges; and
- Underpasses, which consist of culverts and tunnels.

Van der Ree et al. (2008) found great confusion within literature surrounding the interchangeable use of terms when describing crossing structures. In order to provide consistency and clarity when describing mitigation structure, van der Ree et al. (2008) created a table of the general descriptions of structures in the literature. Generally crossing structures are classified as a subcategory; however, when the structures are not classified within this system, the terms 'overpass' and 'underpass' are used.

Type	Description
Overpass	Allows the passage of animals above the road
Underpass	Allows the passage of animals below the major linear infrastructure
Land-bridge	A wide, 30-70m bridge that extends over a road. Land bridges will often have soil, vegetation, rocks, logs and other features to mimic a natural environment and aid animal usage. Land bridges may also be known as 'eco-ducts' or 'wildlife bridges'.
Culvert	Typically square, rectangular or half-circle and may be purpose-built for either fauna passage or water drainage (or a combination of both). Culverts were, by definition, originally intended to carry water; however, engineers and road designers suggested the continued use of the term culvert as this underpass shares a similar structure.

Tunnel	A round pipe of relatively small diameter. May also be known as an 'eco-pipe'.
Bridge	A bridge is a structure that maintains the grade of the road or elevates the traffic above the surrounding land, which enables animals to pass under the road.
Glider pole	Vertical poles placed in the centre of a median or on the road verge, providing species that glide and intermediate landing or launch opportunity.
Canopy bridge/rope bridge	A rope or pole that is suspended above a roadway, usually between vertical poles or trees. Canopy bridges are targeted for use by arboreal or scansorial species.

Table 1: Crossing structure classification (van der Ree et al., 2008)

2.3 Crossing structure studies in Australia

Numerous studies have been conducted into wildlife crossing structures in Australia. This portion of the literature review will involve summaries of studies in Australia where koalas or marsupial gliders have been observed using a crossing structure or targeted to use a crossing structure. Outlined in each summary will be details about the study, including location, habitat, length of study, the type and number of crossing structures, as well as the methodology, results/findings and recommendations from within the paper.

Overpass usage

Overpasses are the general term used to describe crossing structures that enable animals to travel above a road. This term overpass is broad, with this definition including structures such as, but not limited to, land-bridges, canopy bridges and glider poles. The most common type of overpass that is described within literature are land-bridges. Multiple land-bridges exist in Australia, including Compton Road and Hamilton Road. While overpasses and land-bridges may be the only form of a mitigation structure in an area, every Australian example of these overpasses and land-bridges also features several other crossing structures, such as culverts and glider poles. As such, these structures will be reviewed in section 2.4 of this literature review.

Canopy bridge and glider poles

Canopy bridges, also referred to as "rope-bridges", are a common mitigation structure that target use by arboreal or scansorial species. These structures usually consist of two or more trees or hardwood poles linked together by rope that can be joined by a range of configurations or designs, such as "single rope" or "rope mesh". Similarly, glider poles are another mitigation measure that utilise hardwood poles to potentially connect fragmented habitat. Below are several Australian studies that involve the use of rope-bridges or glider poles:

Title	Will arboreal mammals use rope-bridges across a highway in eastern Australia?
Authors (year)	Goldingay et al. (2013)
Location	Pacific Highway, New South Wales
Habitat type	Dry and moist open forest
Observed/ target species	Squirrel glider, feathertail glider, common ringtail possum, common brushtail possum
Mitigation structure(s)	Five rope-bridges with three different designs

Five rope-bridges 50-70m long were installed along the Pacific Highway in New South Wales between Karuah and Bonville. The two rope-bridges in Karuah extended over the highway and were a mesh design; the two rope-bridges at Bundah Creek and Bulga Creek were below a land bridge and featured a 'rope mesh' design; and the rope-bridge at Bonville was present on a land bridge measuring 70m by 50m and consisted of ropes extending between 10-m high poles that were 9m apart.

The rope-bridges were monitored over two periods totalling 13 months using digital cameras activated by infrared motion sensors, in which the date, time, species and position on the rope-bridge were collected. Native mammals were detected on four of the five rope-bridges: feathertail gliders were observed at three locations on three rope-bridge designs; sugar gliders were observed at two locations and on two designs; and squirrel gliders were observed at one location on two rope-bridges of the same design. Several species of possums and the introduced black rat were also observed. The most frequently used rope-bridges were the over-road rope-bridge at Karuah and the rope-bridge below the land bridge at Bulga Creek.

The use of rope-bridges by six different species, including the vulnerable squirrel glider, shows that rope-bridges can be used to link fragmented habitats caused by roads. Hence, research needs to be done on identifying correct locations for these structures, as well as installing an appropriate number of structures in an area to ensure gene flow.

Table 2: A summary of a study by Goldingay et al. (2013) on rope-bridges at the Pacific Highway, NSW.

Title	Evaluating the success of wildlife crossing structures using genetic approaches and an experimental design: Lessons from a gliding mammal
Authors (year)	Soanes et al. (2017)
Location	A 70-km section of the Hume Freeway between Avenel and Benalla, Victoria
Habitat type	Woodland consisting of eucalypt species
Observed/ target species	Squirrel glider
Mitigation structure(s)	Two canopy bridges and two glider poles

Used genetic approaches to study the effectiveness of canopy bridges and glider poles along a 70km section of the Hume Freeway, Victoria. The two canopy bridges were 70m long in a "rope lattice" design while the glider poles were 15m tall and 50cm in diameter. All four of these structures were installed in 2007, 30 years after the freeway was widened, at sites where the treeless gap across the freeway exceeded 50m. Monitoring occurred for two years prior to the installation of the crossing structures and for five years after. The crossing structures were then compared to three controls: the unmitigated freeway, vegetated medians and non-freeway areas.

It was found that the genetic barrier of the roadway was not a complete genetic barrier, with a strong effect only at one site. It was hypothesized that the presence of corridors alongside the freeway and throughout surrounding landscape facilitated circuitous detours for squirrel gliders. At the single site where genetic structuring was restricted, the installation of a canopy bridge restored genetic flow across the freeway. The change was described as "rapid", detectable within just five years of installation.

Table 3: A summary of a study by Soanes et al. (2017) on rope-bridges and glider poles in Victoria, Australia.

Title	Targeted field testing of wildlife road-crossing structures: koalas and canopy rope-bridges
Authors (year)	Goldingay & Taylor (2017)
Location	Southern Cross University Campus in Lismore, New South Wales
Habitat type	Not listed, although the dominant trees in the immediate area were tallowwoods and forest red gums
Observed/ target species	Koalas, possums, squirrel gliders
Mitigation structure(s)	Four different designs of rope-bridges

Monitored four different designs of rope bridges: a rope-ladder that wrapped around an internal structure (45cm wide); a woven rope-mesh with a 1-cm gap between strands (34cm wide); a rope ladder wrapped around internal to produce a sausage shape (28cm wide); and a three-sided rope bridge consisting of a woven-mesh bridge with rope-ladder sides (51cm wide). Each bridge was securely latched to a tree using 10-mm silver rope positions 5m above ground level. The distance between reference trees (trees that rope-bridges were attached to) ranged from 8-11m.

Monitoring was done by cameras attached to the tree at either end of the rope bridge, which occurred over 2.5 years. No koalas were detected on the rope bridges, but they were detected ascending and descending the reference trees. Mountain brushtail possums and ringtail possums were detected on several of the rope bridges and squirrel gliders were also detected on the reference trees. Hypothesized reasons for the koalas not using the rope bridges are: unsuitable reference trees; the difficulty of the rope bridge attachment design to the trees for the koalas to use; the height of the rope bridges; behavioural preferences towards using the ground instead; and the lack of motivation – or need – to use the rope bridges. It is concluded that rope bridges are unsuitable for koalas and that the structures enabling koalas to cross a road structure on the ground, whether overpasses or underpasses, appear to be more suitable.

Table 4: A summary of a study by Goldingay & Taylor (2017) field testing rope-bridges at Lismore University, NSW.

Title	Can wooden poles be used to reconnect habitat for a gliding mammal?
Authors (year)	Ball & Goldingay (2008)
Location	Padaminka Nature Refuge, Mackay, north Queensland
Habitat type	Eucalypt woodland
Observed/ target species	Squirrel gliders
Mitigation structure(s)	Five untreated hardwood power poles

Observed five untreated hardwood power poles in a 70m gap between two habitat remnants. The poles were 12m high and were located 16-22m apart. Each pole cost $1,945AUD to supply and install. Detection of pole usage was done through tree trapping, pole releases, radio-collars and hair sampling on 24 nights over an 18-month period.

Twenty-two gliders were released onto poles 90 times, with 73% using a horizontal bar (which simulates a branch) to glide. All 22 gliders were able to climb the pole and 14 landed on another pole at least once during the release. One glider fell short but then ascended another pole and was able to glide. Male gliders climbed more quickly onto the poles when released compared to females. While the poles were mostly successful, 15% of gliders fell short of their target but continued to walk the rest. Eight gliders that glided to a non-home remnant were later recaptured in their home remnant on 17 occasions. Two individual gliders that were tracked using radio-collars were observed using the glider poles. Hair from hair sampling was also observed on all poles during monitoring.

The observations from this study suggest that wooden poles can assist gliding mammals to open areas between habitat patches. Glider poles proved to be a cheap yet rapid technique for potentially connecting severed habitat.

Table 5: A summary of a study by Ball & Goldingay (2008) studying glider poles at the Padaminka Nature Refuge, Mackay, north Queensland.

Title	Squirrel gliders use roadside poles to cross a road gap
Authors (year)	Taylor & Goldingay (2013)
Location	Scrub Road, south Brisbane
Habitat type	A dry sclerophyll forest remnant
Observed/ target species	Squirrel gliders
Mitigation structure(s)	Three glider poles

Studied the extension of Scrub Road, south Brisbane that was completed in 2010 and bisected a small patch (<10ha) of remnant dry sclerophyll forest. This remnant has several links to larger remnants. Three, 12m-high glider poles with horizontal crossbars 20 and 40cm below the top of the pole were installed to restore a corridor between a 61m canopy gap.

Cameras were used to monitor detection on each pole over 310 operational nights. Gliders were observed on one or both of the poles on 60 out of the 310 operational nights, at an average of 5.2 gliders per night. Over the 125 nights that cameras operated on all glider poles concurrently, gliders crossed the Scrub Road on at least 16 occasions.

This study is the first definitive evidence that gliders will use roadside glide poles to cross a two-lane road. However, further research needs to be done on larger roads where poles are required in the median strip.

Table 6: A summary of a study by Taylor & Goldingay (2013) assessing glider poles over Scrub Road, south Brisbane.

Underpass usage

Underpass is the term used to describe crossing structures where an animal moves below a road. Structures that move below a road may be called 'underpasses' or 'culverts'. Below are summaries of two studies conducted on an underpass and a culvert in Australia:

Title	Movement of small mammals through a road-underpass is facilitated by a wildlife railing
Authors (year)	Goldingay et al. (2018)
Location	The Oxley Highway deviation at Port Macquarie, New South Wales
Habitat type	Open sclerophyll forest
Observed/ target species	Black rat, brown antechinus, brushtail possum, koala
Mitigation structure(s)	Seven 30m-long fauna underpasses, three of which contain an earthen floor and wildlife railings termed "furniture" and the other four having a concrete floor

Wildlife underpasses are commonly fitted with timber railings to facilitate the passage of arboreal and scansorial mammals; however, there have been no published accounts of this railing use. These timber railings attempt to make the underpass a more natural link between habitats and are often termed "furniture". The first recorded use of timber railings in an underpass was during the east Evelyn Road upgrade in 2001.

Use of railings in two of the underpasses was compared to animals using the ground in other underpasses. Railings were monitored for between one and 3.4 years with four species being observed: black rats, brown antechinus, brushtail possums and koalas. The black rat was detected in two underpasses on the ground on six nights, but on 180 nights on the timber railings in the one of the underpasses. Both the brown antechinus and brushtail possum were observed on railings and on the ground in the underpasses, although brushtail possums using the railings occurred infrequently. However, contrary to this, koalas were observed in three underpasses on 11 separate occasions but never used the timber railings – rather only using the ground to move through the underpass.

This study attempts to highlight how different animals utilise a crossing structure. While some species prefer to use the timber railings that provide a more natural passage for the animal, others will use the floor. More research needs to be conducted into the behavioural choices an animal makes when choosing what to use.

Table 7: A summary of a study by Goldingay et al. (2018) assessing the using of wildlife railings in a road underpasses, Port Macquarie, NSW.

Title	Cutting the carnage: wildlife usage of road culverts in north-eastern New South Wales
Authors (year)	Taylor & Goldingay (2003)
Location	Brunswick Heads Bypass, north-eastern NSW
Habitat type	Swamp sclerophyll open forest and woodland
Observed/ target species	Koalas, possums, gliders, as well as bandicoots, wallabies, cane toads, echidnas, lizards, birds, frogs
Mitigation structure(s)	14 fauna culverts, nine of which were assessed

Investigated nine fauna culverts along a 1.4km section of the Brunswick Heads Bypass. Overall there were 14 culverts along the whole 2.5km route, but as several of the culverts were difficult to access and were prone to frequent flooding, only those that could be readily monitored were chosen. These culverts were 2.4m wide, 1.2m high, 18m long and were lined at both sides with a 180cm high chain-mesh fauna-exclusion fence, termed a "floppy top".

Monitoring was done by sand tracking, trapping, spotlighting and roadkills over varying timeframes. Sand tracking showed 1,202 traverses over 16 days, with two of the traverses caming from koalas. Capturing caught 104 individual animals consisting of 10 different species. Thirteen vertebrate species were detected by four evenings of spotlighting; koalas and squirrels were both observed when spotlighting. During the 20 weeks of monitoring, seven roadkills were observed. In

total, 17 vertebrate species used the nine culverts. Overall, culverts within this study proved to offer safe passage below a road for several species, including koalas.

Table 8: A summary of a study by Taylor & Goldingay (2003) assessing the use of culverts in northeast, NSW.

2.4 Multi-structure review papers

While a large portion of the literature concentrates on one crossing structure in an area, some studies quantify the use of multiple different crossing structures across a region. In Australia there are several major wildlife overpasses that feature the use of multiple types of crossing structures, such as Compton Road in Queensland, Hamilton Road in Queensland and Bonville in New South Wales. Each of these regions consists of several different types of crossing structures that attempt to target different species. These structures often provide great insight into various aspects of crossing structure usage, such as seasonal trends and species preferences.

Compton Road, Queensland

The crossing structures of Compton Road, Queensland are an internationally recognised example of a holistic crossing structure. A section of Compton Road separates the 950ha remnant of Karawatha Forest and a 140ha remnant of Kuraby Bushland (Taylor & Goldingay, 2012). In 2004, a 1.3km stretch of road between these two areas was upgraded from two to four lanes and in 2005 the upgrade was completed along with an array of crossing structures. This upgrade, shown in *Figure 4*, included a 70m land-bridge spanning the entire width of the new road, a series of glider poles on the land-bridge, three rope bridges between the tree canopy of either side of the road, two faunal underpasses with wildlife "furniture", three wet culverts and roadside exclusion fencing (Bond & Jones, 2008). The Compton Road land-bridge is a fully-vegetated structure (Jones, 2010) with well established vegetation on either side contiguous with the adjoining forest (Taylor & Goldingay, 2012). The vegetation on the land-bridge consists of thick, dense shrubs and tall emergent trees that had reached a height of eight metres in 2010 (Taylor & Goldingay, 2012).

Figure 4: Compton Road land-bridge located in southeast Queensland. Image from Bond & Jones (2008)

Following the construction of the Compton Road mitigation structures, surveys were conducted to test pre- and post-construction conditions. In a 4-month survey prior to construction, 13 terrestrial vertebrates of 10 different species were killed on the road. However, only two animals were killed over 4-month survey post construction and an additional five animals in the subsequent 29 months (Bond & Jones, 2008). Out of these five roadkills, however, two deaths were attributed to holes in the exclusion fencing—an issue caused by vandals (Bond & Jones, 2008).

Although the immediate success of a crossing structure may not be an accurate depiction of the natural events occurring—for example, Mata et al. (2005) found that some animals were still habituating a crossing structure four years after implementation—it is still significant in that animal deaths were reduced, albeit while fewer species may have used the crossing structure. However, the success of a well structured and well vegetated crossing structure is widely acknowledged (e.g. Jones, 2010; Taylor & Goldingay, 2012), with a particular study on Compton Road by Jones et al. (2011) highlighting the significance of a fully-vegetated land-bridge for arboreal species.

While studies have assessed the overall impact of the Compton Road structure, a large portion of literature on the Compton Road crossing structure focuses on individual components of the crossing structure. Much of the research on the Compton Road crossing structure focuses on the glider poles, which are eight, 6-7m high hardwood poles 30cm in diameter with a gap between poles of 10-12m (Goldingay et al., 2011). In a 42-month survey conducted by Goldingay et al. (2011), glider hair was found on the poles during 83% of the 30 sampling sessions and on all eight poles in 54% of pole-sample sessions. An infrared camera detected a squirrel glider on a pole on five nights, with all of these observed gliders being female. Similarly, Taylor & Goldingay (2012) used hair detection, camera detection and radio-tracking techniques to assess glider use on Compton Road. Taylor & Goldingay (2012) found that over 150 operational camera nights, squirrel gliders were detected on 46 occasions during 40 of the operational nights. Ten radio-collared squirrel gliders were located on 637 occasions at night during the 2007/2008 monitoring period, with three squirrel gliders recorded as being on the opposite side of the road to their original record. During the 2010 radio-collar monitoring period, a male squirrel glider was observed using the land-bridge on three occasions with his movements alternating between using the glider poles and either thick shrubs or tall emergent trees that have grown on the land-bridge. The frequency of hair on the glider poles also increased over time.

Hamilton Road, Queensland

The Hamilton Road land-bridge is another significant multiple feature mitigation structure in Australia. Hamilton Road severs a number of locally significant remnant bushland dominated by dry sclerophyll forest (Taylor, 2010). The Hamilton Road land-bridge is 36m x 15m structure surrounded by exclusion fencing and features local endemic shrubs along the extent of the structure *(Figure 5).* Also present on the land-bridge are six 6.5m-high hardwood poles 20cm in diameter (Taylor, 2010; Goldingay et al., 2011). Hair sampling studies have been conducted on the glider poles on the Hamilton Road land-bridge, showing that over a 16-month period and 16 sampling sessions that hair was found on poles during 69% of sampling sessions (Goldingay et al., 2011).

Figure 5: Image of the Hamilton Road land-bridge, Queensland. Image from Goldingay et al. (2011)

Bonville, New South Wales

The Bonville Pacific Highway upgrade involved building a 9.9km four lane divided highway in order to provide 17.5km of uninterrupted dual carriageway between Urunga and Coffs Harbour (NSW RMS, 2014). The structures present in this upgrade were:

- A 60m-wide, vegetated fauna overpass;
- Four fauna underpasses featuring fauna friendly furniture, specifically for koalas;
- Wide vegetated medians that maintained roadside vegetation for gliding species; and
- Ten kilometres of temporary fencing, whereafter 15km of permanent fencing was erected prior to the completion of the upgrade.

Monitoring was conducted by the New South Wales Roads and Maritime Service (2014) for six years: two years pre-construction, two years during construction and two years post-construction. The key findings from this study were that highways and cleared land tended to become home range boundaries for koalas. Furthermore, koalas killed on

roads showed a seasonal trend to dispersal and breeding season, which occurs between August and October. The final major finding was that the majority of koalas killed on roads were young, dispersing koalas and old "resident" koalas that may have been displaced from their former home range.

Studies over a region

Whereas the studies of Compton Road and Hamilton Road focus on the crossing structures at the site, other studies have been conducted to test a range of crossing structures over a broad area. A study by Dexter et al. (2016) studied six sites across various jurisdictions of southeast Queensland. These six sites received retrofitted upgrades, as follows:

- Site 1 – Koala overpass: purpose-built steel gantry with fauna fence (*Figure 6*)
- Site 2 – Three 3x3m box culverts: a "dry ledge" with a fauna fence
- Site 3 – Two bridge underpasses: fixing of the existing fauna fence
- Site 4 – Four open bridge underpasses: dry ledges built on all four underpasses (*Figure 7*)
- Site 5 – Large open bridge underpass: fauna fence added and revegetation under the bridge
- Site 6 – Open bridge underpass: fauna fence with gravel fauna pathways added

Figure 6: Modified steel gantry with poles connected to either end of the overpass to become a purpose-built koala overpass. Image from Dexter et al. (2016)

Figure 7: A wooden dry ledge in one underpass with a koala using the structure. Image from Dexter et al. (2016)

Koalas were captured within a ~1.5km² area of each retrofitted and were monitored using a range of techniques, including GPS collars, camera traps, sand plots and RFID tags. In total, 72 different koalas were fitted with some sort of monitoring device. Monitored koalas were tracked over a 30-month period from September 2010 to August 2012. Over this period, 130 crossings were recorded over a crossing structure or a road by 15 tagged koalas – 11 of which were male and four female. Koala crossings on the road were detected at all six sites, while crossings over a retrofitted structure occurred at three sites. Untagged koala crossings were also detected. This study by Dexter et al. (2016) showed that koalas would willingly incorporate structures into their movement patterns. It also emphasizes the benefits of using complementary data collection – that is, multiple different monitoring methods. This use of complementary data collection minimises data loss while also providing more accurate data.

2.5 International literature

The focus of this research relies on Australian studies due to similarities in target species and habitat which would drastically differ overseas. However, while not entirely relevant in these regards, international literature can still provide great insight into various trends that may be observed and could be important to this study and for future research.

One of the most significant findings amongst international literature is the differential structure usage and the variable seasonal usage of crossing structure types between seasons. Best highlighted within the works of Mata et al. (2005; 2008; 2009) on studies of the A-52 Motorway in northwest Spain, animals that are exposed to numerous crossing structures will use many of these structures when travelling throughout their home ranges. In Mata et al. (2005), 82 crossing structures were studied over a 71.5km stretch of the motorway. Throughout the 3-month study period, the tracks of 1,122 species of 17 different taxa were observed, equating to 1.37 species crossing per crossing structure per day. Small mammalian species in the study were recorded using every type of crossing structure, including culverts, underpasses and overpasses. Similarly, Mata et al. (2008) studied 39 crossing structures along a 57km section of the motorway. A total of 17 different faunal species were observed, with a total of 424

animals recorded over a 2-month period, equating to 0.99 species passing per crossing structure per day. All crossing structures were used, with overpasses being the most used structure and two types of culverts being the least frequently used. However, the most common structure used by small mammals was circular culverts.

Furthermore, Mata et al. (2009) also showed that while species will use a range of crossing structures, the use of these structures varies seasonally. Mata et al. (2009) studied 48 different crossing structures over a 55km stretch of the motorway. This study showed that six of the 19 species observed showed seasonal variation in road crossings, with one of the six being more frequent in winter with the other five being found to cross more in summer. Wildlife overpasses were less used in summer, with the other structures being used more in winter. There was a preferential use of passages under the road in the summer substituting the use of overpasses in the winter. Species in this study also showed preference to crossing structure types. Small mammals, especially, showed significant differential usage of crossing structures, which varied between seasons. Two main reasons for these seasonal trends were hypothesized: firstly, increased traffic in the summer may prevent use of overpasses by the animals; and secondly, water run-off may reduce the use of riverbeds by animals and cause culverts to become flooded at "low" positions. Increased traffic levels in summer months also leads to an increase in average noise level, further forcing animals not to travel above a road.

2.6 Alternative mitigation measures

While overpasses and underpasses are the most common mitigation measures, these structures may also be used in conjunction with other mitigation methods. One such mitigation measure is exclusion fencing. Whereas mitigation structures attempt to reconnect habitats and reduce the effects of habitat fragmentation, exclusion structures attempt to reduce animals entering specific areas or guide and filter them towards desired areas, such as towards a crossing structure or away from a road (Taylor & Goldingay, 2003; 2010).

The importance of exclusion fencing has been shown to great effect. Cunnington et al.

(2014) found that culverts alone did not reduce road mortality and that mortality at sites surrounded by exclusion fencing showed a greater decrease in wildlife mortality. Glista et al. (2009) and Baxter-Gilbert et al. (2015) emphasized that the effectiveness of a crossing structure relies on the surrounding exclusion fencing to serve its purpose. Furthermore, a model-based study by Ascensao et al. (2013) found that exclusion fencing was much more important in mitigating the effects of roads than crossing structures were. Overall, exclusion fencing can be seen as being an integral part of a mitigation structure (Rowden et al., 2008).

While exclusion fencing is an effective way to filter animals towards a crossing structure or move them away from roads, it does have its setbacks. The overall goal of exclusion fencing is to reduce mortality; however, creating more barriers to species movement may exacerbate habitat fragmentation (AMBS, 2012). A significant amount of exclusion fencing also has to be present at a site for effective results, as short fence lengths have lower and more variable effectiveness than long fences (Huijser et al., 2016). Exclusion fencing is also a significant cost at $180 per metre (Dexter et al., 2016) and short lengths of exclusion fencing that may be utilised to cut costs would severely compromise the effectiveness of this mitigation measure.

Exclusion fencing, or "guide fencing", as it is also called within literature (Taylor & Goldingay, 2003) does just that—guide species towards a certain area. Frequent movement of animals to a specific area may result in prey traps being formed with opportunistic predatory species prying on a frequent flow of possibly vulnerable animals (Taylor & Goldingay, 2003). Although conjecture exists around if prey traps truly do exist in the natural environment near mitigation structures, a major review paper by Little et al. (2002) stated that while much of the evidence of prey traps is scant, anecdotal and does not show recurring patterns, they did not deny that a greater concentration of animals in or around a crossing structure was beneficial for opportunistic predator species.

Apart from exclusion fencing which attempts to filter animal movement towards a crossing structure or force animals away from a road entirely, other measures may be used. One such method is the use of signage, which can be used to change traffic conditions or alert drivers to the presence of animals in close proximity to the road.

Studies on the effectiveness of signage, however, have shown mixed success. In a study conducted by Dique et al. (2003), differential signage was erected in six study sites approximately 500m apart, which displayed two different speeds and the time at which they were enforceable. Over the 4-year study period, speed signs did not reduce the collisions of koalas and vehicles; rather, the number of roadkills steadily increased each year over the study period and was greater than the number of roadkills in a pre-study year. Similarly, a study by de Villiers (1999, as cited in NSW RMS, (no date)) observed reduced speed zones between the months of August and December from 7pm to 5am – the times when koalas are most likely to be moving on the ground. This study, conducted in southeast Queensland, had limited success in reducing car speed. Other methods to change traffic conditions have also been utilised throughout Australia. Roadside reflectors, speed humps, wildlife repellents, roadside lighting and light-coloured road surfacing have all been tried in Australia with mixed success (Magnus et al., 2004; Rowden et al., 2008; Rytwinski et al., 2015).

More alternative mitigation measures have been utilised overseas. One such method is the use of activated roadside signage when a species is observed on roadside monitoring cameras or activated automatically when an animal triggers a roadside sensor. Mitigation measures similar to this are extremely prevalent overseas to combat deer populations (Hedlund et al., 2004). Although the immediate success of these measures is noted, the cost and scale at which they operate cannot currently be transferred to a larger scale, and the potential for false positives and lack of driver response also presents challenges (Hedlund et al., 2004).

2.7 Determining success of crossing structures and other mitigation measures

One of the most difficult aspects of crossing structure studies is determining the success that the structure had or is having. The information that is being collected for these studies depends on that study at hand. There is not a universal approach in determining the success of a crossing structure; thus, several other aspects of methodology in the literature must be critically analysed. These include: monitoring before and after structure installation; the overall length of the study; the criteria for selecting and

installing crossing structures; and the factors that affect crossing structure use which vary seasonally and geographically.

The timeframes regarding crossing structure installation and monitoring vary drastically. In a review paper by van der Ree et al. (2008), only 11 of the 59 studies reviewed compared before and after scenarios when a crossing structure was installed. Corlatti et al. (2008) noted that while literature for assessing the use of mitigation structures is abundant, there is a lack of evaluating species characteristics, such as dispersal, before and after a mitigation structure is installed. Studies were also not explicit in stating when the structure was built and when monitoring following installation of the structure began. The length of monitoring within studies also differs. In reviewed papers, monitoring of mitigation structures ranged from 12 hours of spotlighting (Taylor & Goldingay, 2003) to seven years of before and after crossing structure installation monitoring (Soanes et al., 2017). This gives rise to a major issue: seasonal variation in crossing structure usage. As outlined previously, some studies (e.g Mata et al., 2009) have specifically shown that crossing structure usage varies seasonally between species. Therefore, if studies do not explicitly state the monitoring/observations periods over which they have conducted their study, questions can be raised as to whether or not the study encapsulated what is actually occurring in the area. Studies conducted over short time periods, such as those that occur over only several weeks or a few months, can thus be seen as an insufficient timeframe to capture natural events, especially in regard to seasonal trends, and are unable to quantify the impact prior to mitigation (Soanes et al., 2013).

Furthermore, structures are rarely field-tested which results in poor designs constantly being reused and a subsequent lag time in design advancement (van der Ree et al., 2008). While some studies are explicitly trials for different types of crossing structures – for example, a study by Goldingay & Taylor (2017) field-tested different designs of rope bridges at the Lismore University campus prior to possible installation elsewhere – other studies do not state the reasons for choosing and/or installing a crossing structure. The existing approach to road mitigation is to simply adopt best practice in the field, which includes type, number and location of mitigation measures. While this

approach does identify the best mitigation structure to be installed, it does not facilitate learning about the effectiveness of the mitigation measure (Rytwinski et al., 2015).

Additionally, the frequency at which road mortality mitigation measures are implemented does not correlate with their perceived effectiveness. Mitigation measures that are the most promising are often the least used and measures that have minimal success are frequently used (Glista et al., 2009). For example, road signs are frequently used when the success of this mitigation measure has been shown to have minimal effect on changing driver attitude and reducing wildlife mortality (e.g. Dique et al., 2003). Similarly, more alternate methods such as roadside reflectors and lighting also show little to no effectiveness, yet are still frequently tested and used (Magnus et al., 2004). Lack of information and scientific rigor is also an issue present within this context. Decision-making is often hampered by a lack of information as to the effectiveness of crossing structures (Soanes et al., 2017) and limited available resources means that wildlife managers only focus on single method of mitigation (Ascensão et al., 2013).

Another issue with studies is the lack of thought given to the species involved in the study and the area surrounding a structure. A range of interrelated biological and environmental factors affect an individual or population's decision to use a crossing structure (Kintsch & Cramer, 2011). Environmental factors such as location, habitat, dimensions of the crossing structure, gaps between habitat and the structure (known as the "cover at entry"), other barriers around the crossing structure, climatic variations due to microclimates, elevation gradients and noise from vehicles are often neglected within studies (Glista et al., 2009; Kintsch & Cramer, 2011). These factors are often paramount to the success of a mitigation structure, yet are not extensively looked at within literature.

3. Methods

3.1 Study area

The Sutherland Shire and Campbelltown are two local government areas located to the south of Sydney (*Figure 8*). Covering a total area of over 480km^2 (Sutherland Shire = 369km^2; Campbelltown = 312km^2), these local government areas are host to localities including Holsworthy Barracks, Lucas Heights nuclear base, Woronora Dam and the Georges River.

Figure 8: Map of the study area

Prominent in both the Sutherland Shire and Campbelltown are two national parks: the Royal National Park and Heathcote National Park. The Royal National Park is located 32km south of the Sydney CBD (Ramp et al., 2006). Covering an area of approximately 16,000ha (DECCW, 2011), the national park features habitat types including heathland, woodland, eucalypt forest, rainforest, wetlands and swamps (NSW National Parks and Wildlife Service, 2000; Ramp et al., 2006). With a temperate climate, the national park is home to 50 mammal species (40 of which are native), 241 bird species, roughly 40 reptile species and 30 amphibian species (Ramp et al., 2006). Located to the west of the Royal National Park is Heathcote National Park – a 2,250ha area featuring much of the same habitat that is present within the Royal National Park.

Present in both of these local government areas—and running through these national parks—are several major roads that service movement between Wollongong, the greater Sydney area and western Sydney (*Figure 9*). In the Sutherland Shire local government area, one major road that services movement of people from Wollongong and Sydney is Heathcote Road. Built in 1943, Heathcote Road is a 24-kilometre highway that, over time, has received numerous road upgrades to increase road traffic conditions and safety. According to the Roads and Maritime Services 'Traffic Volume Viewer', Heathcote Road has serviced an average of 23,609 vehicles daily in 2018 (date accessed: 18 June, 2018), with this figure steadily rising from 19,296 vehicles in 2012. Another major roadway, the Princes Highway, which connects onto Heathcote Road, has serviced over 24,000 vehicles daily in a southbound direction only (date accessed: 27 August, 2018). Similarly, there are several major roads in the Campbelltown region to the west, including Appin Road, Wilton Road and the Hume Highway, each of which service tens of thousands of motorists each day travelling between the Illawarra and southwest Sydney.
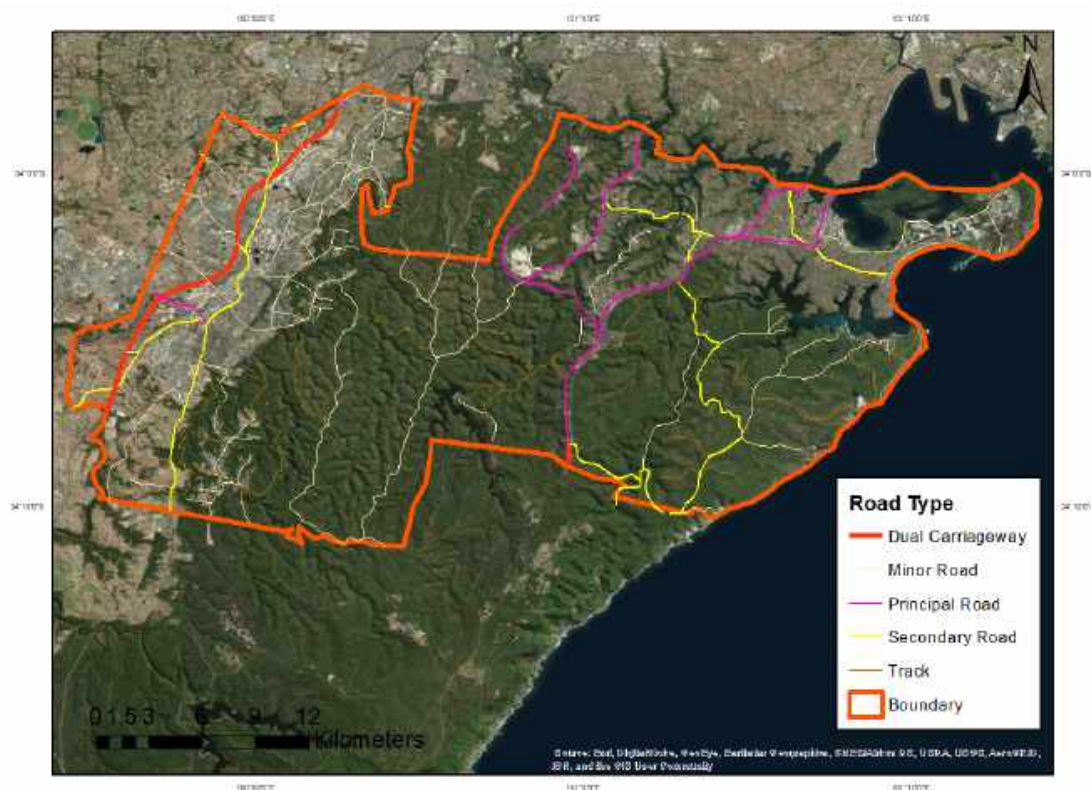
Figure 9: Map of road types within the study area

3.2 Habitat connectivity in the area

These roads, their subsequent upgrades and an increase in the number of daily travellers have caused major disruptions to both flora and fauna, causing extensive habitat fragmentation. As previously mentioned, habitat fragmentation also entails the loss of habitat corridors which enable animals to travel throughout their home ranges – and the loss of these habitat corridors means that many animals are forced onto roadways to travel across these ranges, exposing animals and road user alike to potential injury or death.

The loss of habitat connectivity is a major concern in this region. The Royal National Park, Heathcote National Park and Garawarra reserve complex is one of the better-connected reserves, as it remains proximate to extensive native vegetation (DECCW, 2011). The habitat corridors in this area are extensive, ranging from the Royal National Park to the Heathcote National Park in the west, the Dharawal National Park to the southwest, the wet forests of the Illawarra to the south and other fragmented habitat

patches towards the northwest. A DECCW (2011) paper identifies two major concerns that can threaten connectivity for the species living in this area:

- The major transport corridor – both freeway and railway – that interrupts vegetated links between the Royal, Garawarra and Heathcote reserves, as well as the Woronora Special Area (drinking water catchment).

- The mosaic of cleared and vegetated land between Helensburgh and Stanwell Park, which is a mix of tenures supporting a number of urban and semi-rural land uses. These areas are not managed for natural conservation and, as such, may be vulnerable to increased urbanisation, leading to losses of the habitat corridors that exist between the Royal National Park and the Illawarra escarpment.

3.3 Fire

Habitat fragmentation and loss from urbanisation are the primary driving force for species loss. One other major driving force of habitat and species loss that is prominent in this region is fire. Both the Sutherland Shire and Campbelltown have an extensive fire history. Fire predominantly occurs in two forms: wildfire and prescribed burning. While not much is known about early Aboriginal and early European burning practices, there is undeniable evidence that humans have influenced the fire regimes, resulting in the present composition of vegetation in the area.

The Royal National park has been affected by three major wildfires since 1974, the worst being in 1994 when approximately 90% of vegetation was burnt (DECCW, 2011). Similarly, Heathcote National Park and the Helensburgh area were burnt by a severe wildfire in the summer of 2001/2002. More recently in April 2018, an arson-initiated bushfire tore through the Menai/Holsworthy area, burning a large portion of the Heathcote National Park. High frequency fire (both wildfire and prescribed burning) are listed as being the key threatening process under the TSC Act to species.

Although fire is not a prominent aspect within this study, it is important to identify that fire has played a major role in reshaping the landscape. The role that fire plays on the landscape will continue over time and, as such, will affect species behaviour and

available habitat. Due to disruptions in this area from general urbanisation, roads and fire, with the potential for this to worsen with climate change, areas of concern for species need to be investigated to combat the issues of habitat fragmentation and habitat loss.

3.4 Spatial analysis

Spatial analysis software is an effective way to map and model various observable trends within a dataset. One common trend within this field is the determination of 'hotspots'. The actual definition of the term 'hotspot' varies greatly within literature, with the definition usually being selected based on the specific goals of the study (Nelson & Boots, 2008). One such definition of a hotspot is: "…regions of high density separated from other such regions by regions of low density" (Hartigan, 1975, p. 205). Closely related to hotspots is 'clustering', which is the unusual aggregation of events whereby an intensity threshold is exceeded and thus a cluster is observed (Lawson, 2010). The terms 'hotspot' and 'cluster' are frequently used interchangeably within the literature although both are similarly defined in that they attempt to find areas where an event is more prominent. Hotspot analysis provides a powerful tool for analysing and visualising threats to a wildlife population as it is straightforward to construct and easily communicated (Preece, 2007).

Geographic Information Systems (GIS) software can be used to find hotspots or areas of clustering. GIS software has been used within numerous studies in this field to identify hotspots (e.g. Ramp et al., 2005; Wilson, 2012; Dougherty, 2015) and to choose suitable areas where a mitigation structure (Diaz-Varela, 2011) or signage (Krisp & Durot, 2007; Moshtagie & Kaboli, 2015) could be placed to best offset these hotspots. Using GIS software, hotspots can be found and analysed using several methods:

- Point Density: Calculates a magnitude-per-unit area from point features that fall within a neighbourhood around each cell
- Kernel Density: Calculates a magnitude-per-unit area from point features using a kernel function to fit a smoothly tapered surface to each point
- Get-Is* Hot Spot tool: Given a set of weighted features, identifies statistically significant hot spots and cold spots using the Getis-Ord Gi* statistic

- Optimized Hot Spot tool: Uses the same methodology as the Get-Is* Hot Spot tool but evaluates the characteristics of the input feature class to produce optimal results.

Each of the above tools can be used to find hotspots or clusters within a dataset. While some studies focus on using Point Density (Wilson, 2012), Kernel Density (Morelle et al., 2013) and Hot Spot (Rowand, 2016) tools individually, other studies use several of these tools to compare and highlight differences between each tool (Nelson & Boots, 2008; Sarkar et al., 2014; Dougherty, 2015). Although these tools are relatively similar in nature, some differences do arise. While Point Density calculates the density of a point around each cell output, Kernel Density spreads the known quantity of a population for each point out from the point locations. This results in hotspots with the highest value at the centre which tapers to zero at the end of the hotspot, thus causing a smoothing effect (Sarkar et al., 2014). Contrary to both Point and Kernel Density, Hot Spot tools show both areas that are hotspots and coldspots within a dataset while also generating a statistical output highlighting the significance of that particular data.

Another way in which spatial analysis software can be utilised is for determining areas that are suitable for species within a study area. By combining several feature datasets, areas that are suitable or potentially harmful to species presence and movement can be shown. One such study by Ahmad et al. (2018) combined several key study area features, such as habitat cover, streams and roads, with a range of disturbance factors to show areas of suitability for species.

Maps of this nature can be produced using several methods. One such method is the creation of a simple 'cost surface' to show areas that are unsuitable for species, areas that inhibit movement or to show potential habitat corridors and barriers to movement. Features in several raster datasets can be reclassified and weighted according to their perceived influence on species movement, with each of these reclassified datasets being merged together to generate a final map. By assessing natural and physical features and barriers to species within a study area, locations within the study area that are unsuitable, difficult to traverse or disrupt natural movement corridors for species can be found. When areas that offer some resistance to species movement coincide with areas of high species presence from hotspot analyses, there may be a need to conduct

further research into these areas for the potential implementation of a wildlife crossing structure.

3.4.1 Data

Wildlife data was downloaded on June 20, 2018 from the New South Wales BioNet Atlas – a publicly accessible repository run by the Office of Environment and Heritage (OEH) where species sightings and information relating to these sightings are uploaded to a database. Data was obtained for both the Sutherland and Campbelltown local government areas (LGAs) and sorted according to target species, with data for koalas and all species of marsupial gliders being extracted. An extensive classification list exists for sightings within the BioNet Atlas, with sighting type including animals that were physically observed or heard, trapped, killed by other animals or vehicles, shot and even carcasses or faecal matter observed. Data was sorted into two classes: roadkill and all other sightings. The choice to keep every other sighting type that was not roadkill, including faecal matter and trapped, in an "all other sightings" section was due to this data being individually important to the study. If this data were to be excluded, it may not be an accurate representation of what is occurring as this data could show areas where animals are moving between. Faecal matter, especially, provides some insight into the areas in which koalas are moving between. The final data existed in two spreadsheets – one for koalas and one for marsupial gliders, each of which contained the coordinates of the sighting, the type of sighting (roadkill or all other sightings) and the number of animals observed at each sighting location.

3.4.2 Determining hotspots

ArcMap GIS software (ESRI 10.4.1) was used to spatially analyse the data. The first step was to determine the presence of hotspots, which, for this study, were determined to be areas of high species presence. Due to the small number of roadkills in the available data, the decision was made to analyse the whole dataset to determine hotspots. As aforementioned, a range of tools can be used within ArcMap to find hotspots. Density tools were chosen for this study rather than Hot Spot tools due to being able to produce a simple yet visually appealing output with no numerical outputs attached. The Density tools, which include Point Density and Kernel Density, calculate a magnitude-per-unit

area around a feature and provide a simple visualisation of spatial clustering. The Density toolset within ArcMap is also inline with the motives of this study: to provide an effective but simple foundation by which further research can be conducted. The level of sophistication of the numerical output from Hot Spot tools is beyond the scope of the study.

From the density analysis, the resulting output was split into five equal interval categories and ranked according to their 'level of density'. These levels of density ranged from 'none' to 'significant' and displayed areas where species were clustered within the study area.

3.4.3 Cost surface

In order to find suitable areas of habitat, potential existing habitat corridors and areas that may be difficult to traverse, a basic cost surface of the study area was created using map algebra. The Raster Calculator tool within ArcMap was used to merge the following six reclassified datasets:

- Roads from GEODATA TOPO 250k Series 3 (Geoscience Australia, 2006)
- Watercourses from GEODATA TOPO 250k Series 3 (Geoscience Australia, 2006)
- An "other water" layer that included anything which was not a watercourse, such as dams, lakes and the ocean from GEODATA TOPO 250k Series 3 (Geoscience Australia, 2006)
- Slope, which was reclassified from a digital elevation model (DEM) of the study area
- Native vegetation from OEH (2016) titled 'The Native Vegetation of the Sydney Metropolitan Area – Version 3', downloaded from datasets.seed.nsw.gov.au
- Land use from GEODATA TOPO 250k Series 3 (Geoscience Australia, 2006)

Values for the reclassifications ranged from 1 to 20, with 1 being assigned to the null values within the dataset (any areas that did not have data) and 20 being assigned to any feature that was deemed highly unsuitable to an animals' movement. In each dataset, features with the smallest effect (such as dry sclerophyll forest in the native vegetation dataset and tracks in the roads dataset) were given a value of 2, with the

next greatest feature being given a 3 and so on. In the native vegetation and land use layers, features deemed to be of similar influence on a species were clumped together and assigned the same value due to the difficulty of ranking these similar features. As the scope of this study was focusing predominantly on the influence of habitat/land use and roads, any feature deemed to be unsuitable within these datasets were assigned a weighted value of 3 (or *3) to their original value to emphasize the influence of these features within this study. The only variations from this occurred within the watercourses dataset, with major streams being assigned a weighted value of 3 due to their greater ability to restrict animal movement than minor streams, and also slopes greater than 50^0 being given a value 3 higher than that of the next lowest slope class due to the increased difficulty to traverse steep gradients.

The original data layers, along with the reclassification values for each feature, can be found in **Appendix 1** through **Appendix 5**.

4. Results and discussion

4.1 Hotspots of koala presence

Using the data downloaded from the NSW BioNet Atlas, koala sightings were sorted according to koalas killed by vehicles and all other koala sightings (*Figure 10*).
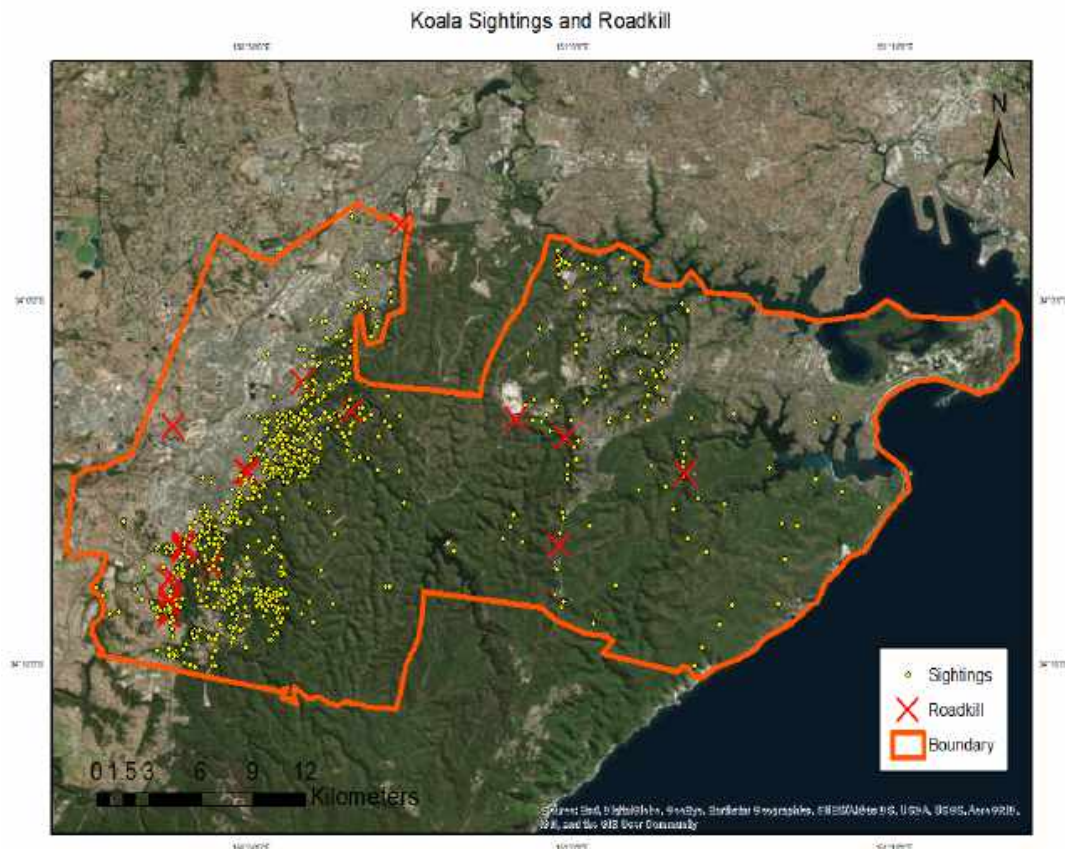
Figure 10: Koala sightings and roadkill records from the NSW BioNet Atlas.

In total, 1,442 koalas sighting locations were on record with 23 of those sightings being individual koalas that were killed on roads. The remaining 1,419 sightings included any other recorded sightings.

Using the Point Density tool within ArcMap, koala density was then mapped for all 1,442 sighting locations (*Figure 11*). The variable being analysed within this tool was the number of koalas at each sighting location as more than one koala was observed at some sighting locations. The spatial extent of the output was also kept to default, as changes to the cell area would alter results.
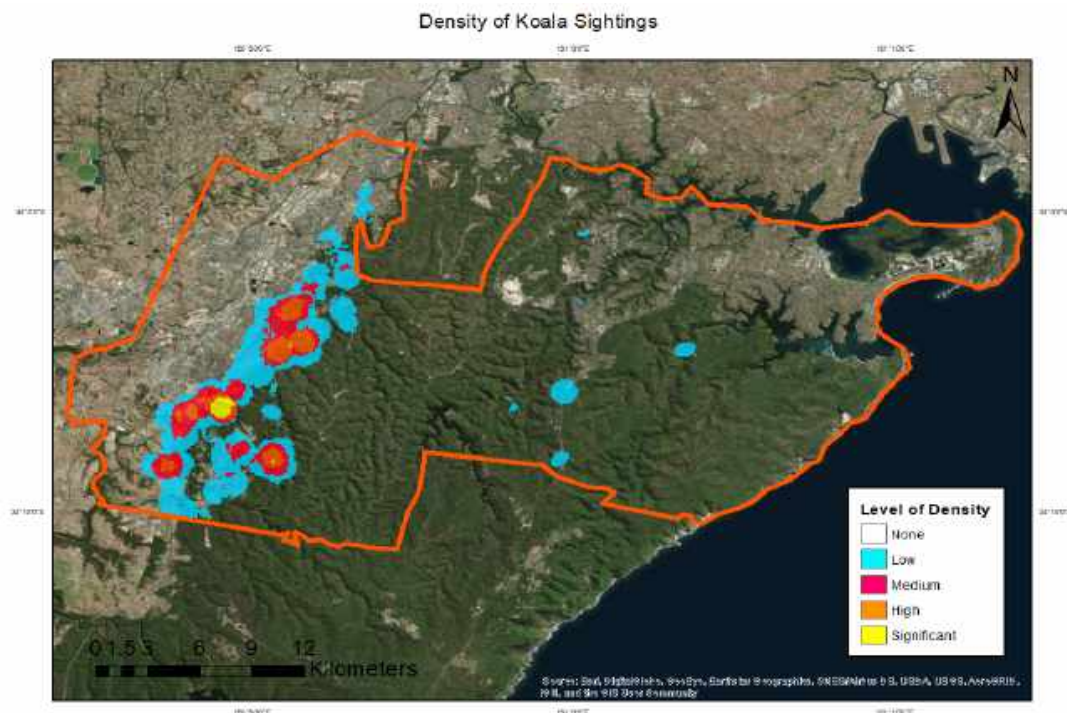
Figure 11: Koala hotspots, identified using the Point Density tool across the whole koala sighting dataset

Koala hotspots were classified over five classes using the equal interval classification, ranging from 'none' (transparent) to 'significant' (yellow). From the Point Density analysis, 11 main koala hotspots can be observed along with several other smaller neighbouring hotspots. Using an equal interval classification, seven hotspots were deemed to be of a 'high' level of density. When the Point Density output is plotted with each of the koala sighting locations (*Figure 12*), hotspots can be seen to be occurring within the expected areas.
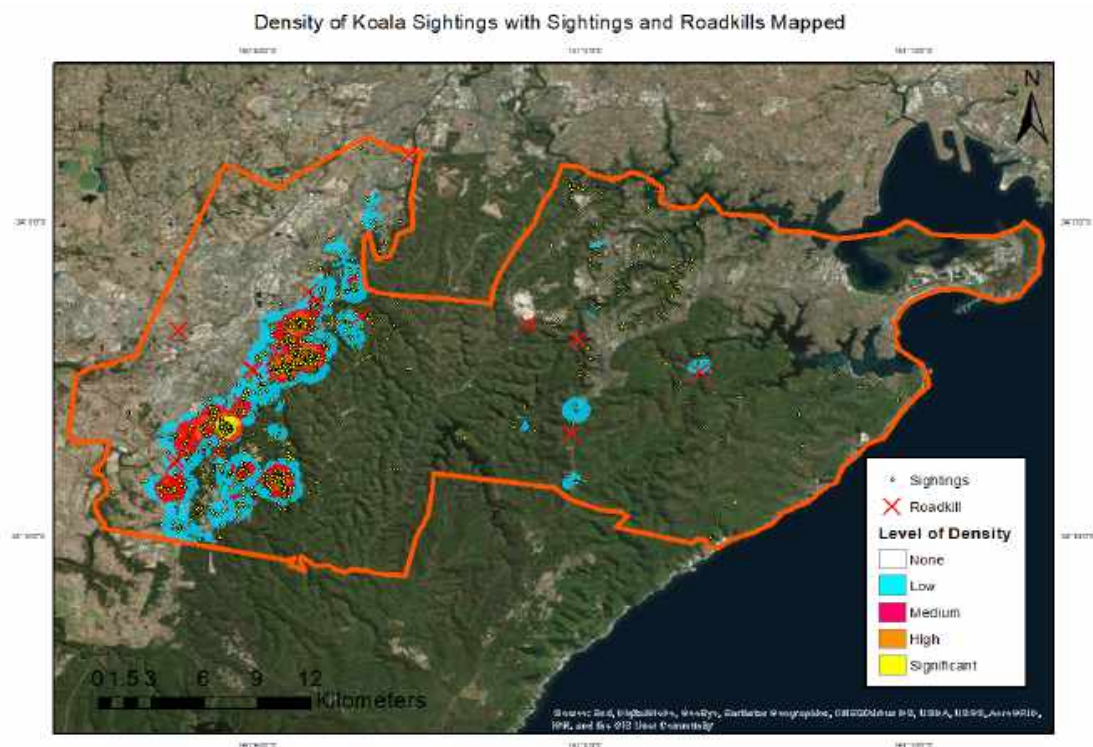
Figure 12: Output of Point Density analysis mapped with koala sightings and roadkills

When analysing significant clusters in proximity to roads, the following map is produced:
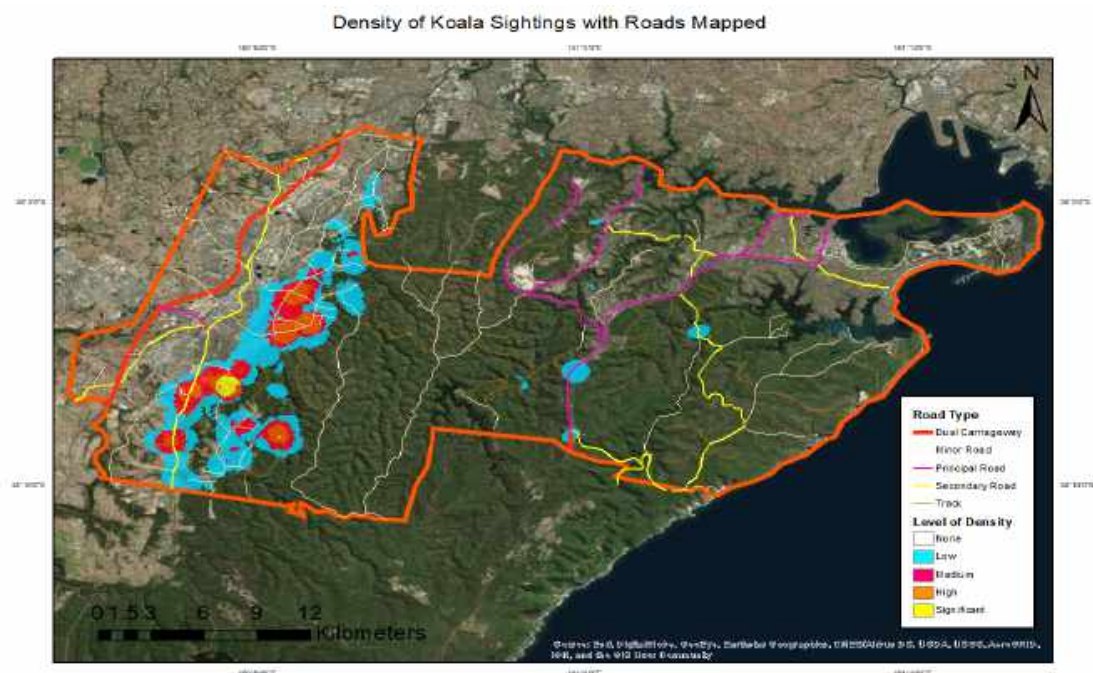
Figure 13: Output from Point Density analysis mapped with roads

Upon inspection of the above figures, it can be seen that most spatially clustered areas of koalas occur in the Campbelltown region of the study area. When observing *Figure 13*, two clusters can be seen towards the southwest portion of the study area. This road, Appin Road, is shown in *Figure 14* along with koala sightings and roadkills.
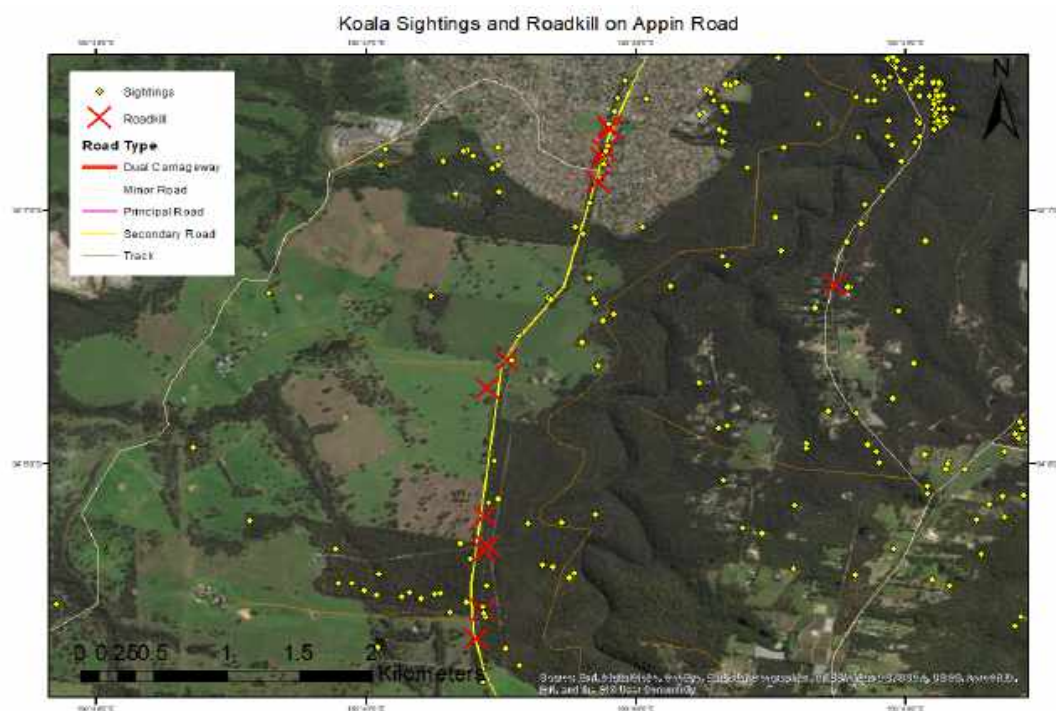
Figure 14: Koala sightings and roadkills around Appin Road, NSW (number of roadkill = 12).

In the above figure, 12 koala roadkills can be observed on a 3.8km stretch of Appin Road. The 12 koalas killed on this segment of road make up over half of the 23 koala roadkills that were found within the study area. This segment of road has several key habitat features:

- Largely intact, mature dry sclerophyll forest to the east with a waterway;
- Small, remnant patches of dry sclerophyll forest to the east of the road surrounded by pastoral land;
- A residential area to the north; and

- Appin Road (while no traffic data exists for directly on Appin Road, the nearest traffic survey site in Campbelltown has over 25,000 vehicles using this area each day).

Out of the 12 roadkills observed on this road five occurred in the residential area, two occurred on cleared land that is now pastoral land and five occurred near the relatively intact section of mature forest to the east of the road. While roadkills in this area are significant, it is also noticeable how frequent sightings are in this area. Koalas are not only observed in the dry sclerophyll forest to the east, but also in the remnant patches amongst pastoral land as well as remnant patches around the residential area.

When the koala roadkills in this area are mapped with the original hotspot analysis, *Figure 15* is produced. Out of the 12 koala roadkills, 10 of the roadkills exist within two hotspots from the previous analysis for the whole koala dataset.
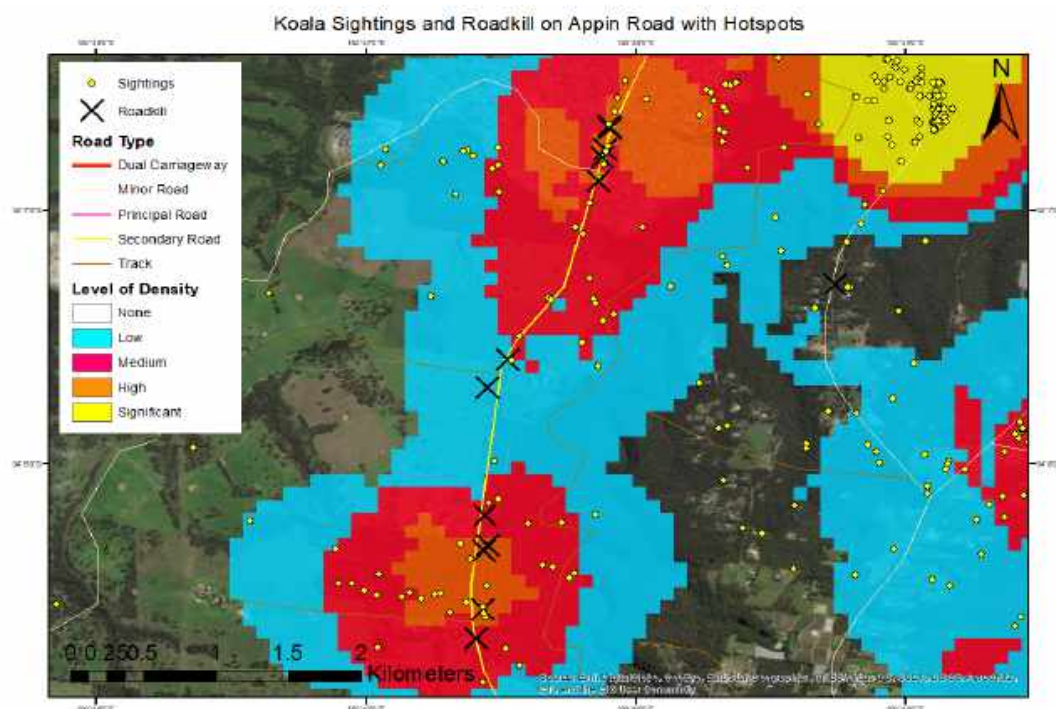
Figure 15: Koala roadkills and sightings on Appin Road mapped over the original Point Density analysis.

4.2 Hotspots of marsupial glider presence

Using the data downloaded from the NSW BioNet Atlas (as of June 20, 2018), glider sightings were sorted according to gliders killed by vehicles and all other glider sightings (*Figure 16*).
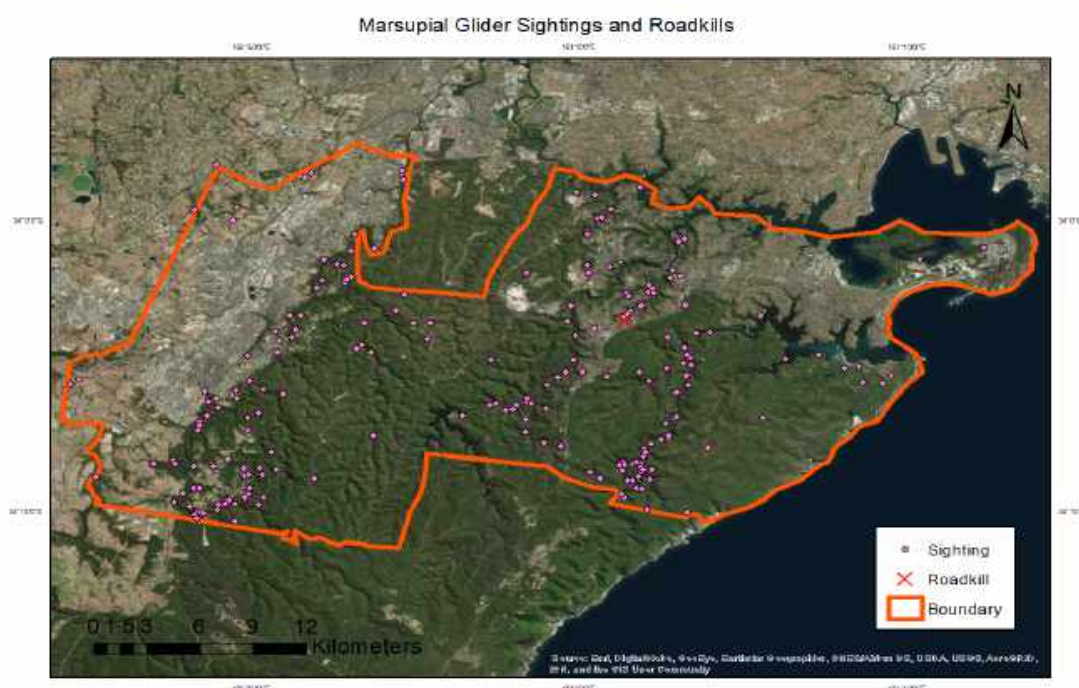
Figure 16: Gliders sightings and roadkill records from BioNet Atlas

In total, 325 marsupial gliders have been observed on the BioNet Atlas records. Out of the 325 glider sightings only one roadkill was observed – a squirrel glider killed by a car on Heathcote Road. As not all glider sightings were the same glider species, gliders were then mapped based on species, as shown in *Figure 17.* Table 9 presents the breakdown of marsupial gliders by species.
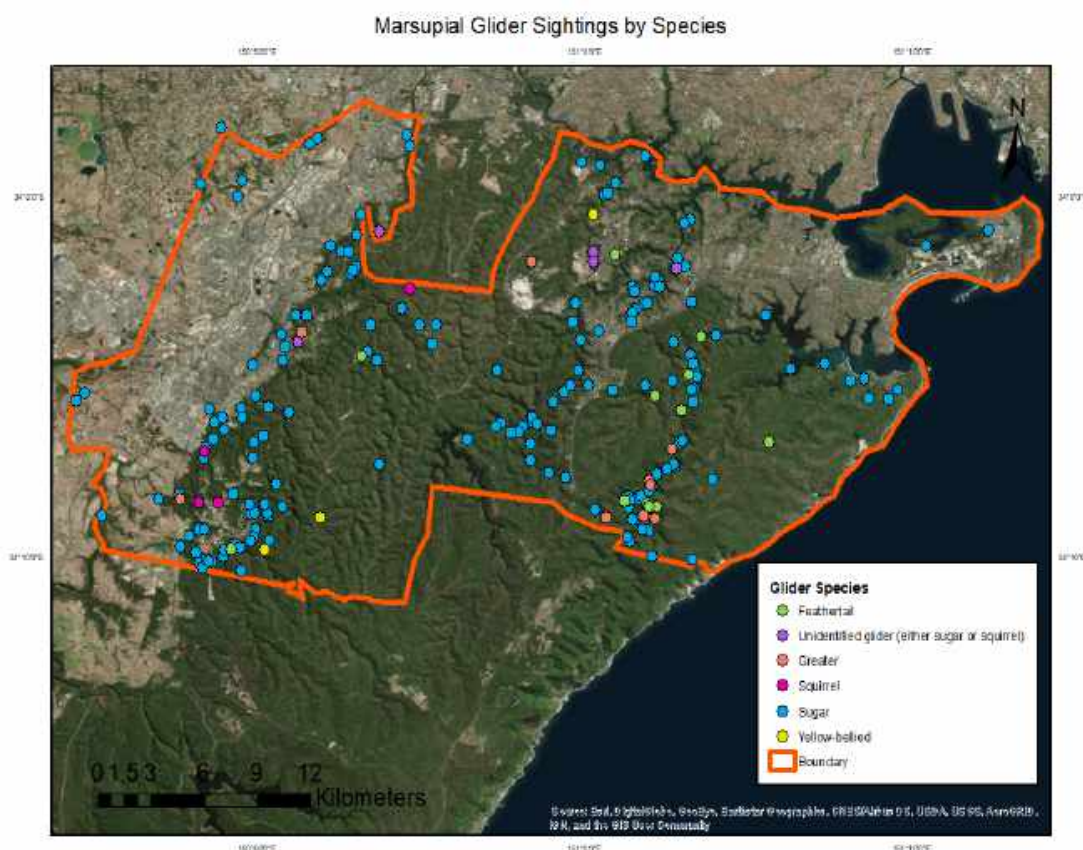
Figure 17: Glider sightings by species

Glider species	Number of sightings	Number of roadkills
Feathertail	12	0
Unidentified (sugar or squirrel)	8	0
Greater	12	0
Squirrel	4	0
Sugar	284	1
Yellow-bellied	5	0

Table 9: Breakdown of glider sightings by species

As can be seen in the above table, sugar gliders are the most common glider species within the study area.

Using the Point Density tool, glider hotspots were analysed (*Figure 18*).
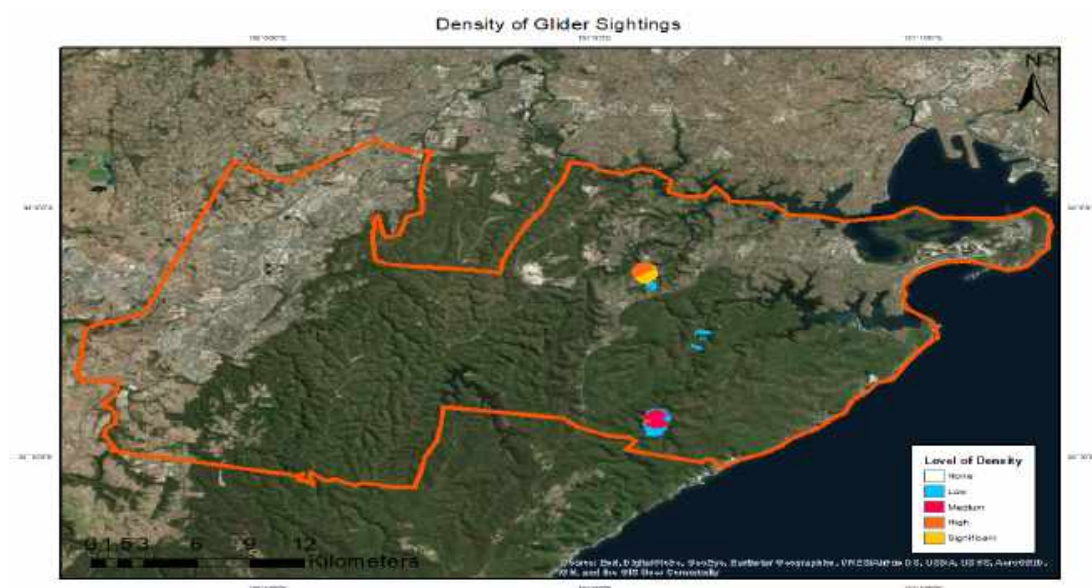
Figure 18: Glider hotspots using Point Density tool

As can be seen in *Figure 18*, two glider hotspots are observable using Point Density analysis. Due to the small size of the density output using Point Density, the Kernel Density tool was also used. Contrary to Point Density, Kernel Density attempts to adjoin spatially clustered areas with smooth shading between the two dense areas. *Figure 19* is produced when using the Kernel Density tool.
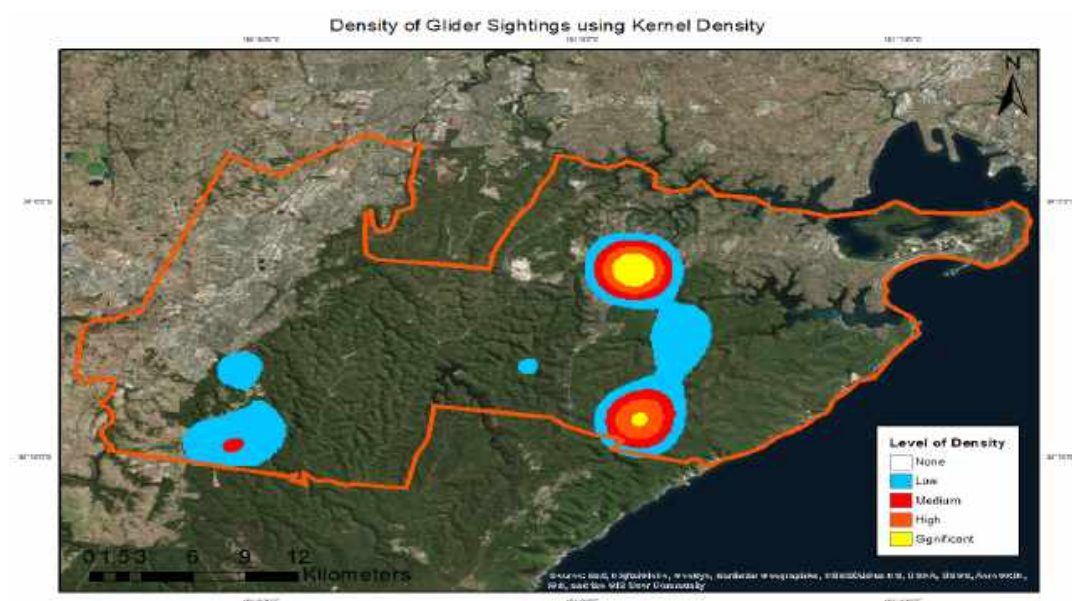
Figure 19: Glider hotspots using Kernel Density tool

From the Kernel Density analysis, two major hotspots are observable which are connected through Kernel Density's smoothing effect. A smaller hotspot is observed to the southwest of the study area. Contrary to the Point Density tool, Kernel Density created much larger hotspots with an evident smoothing effect, as well as generating a third hotspot which was not present previously. When the output from the Kernel Density tool is mapped along with glider sightings and roads, *Figure 20* is produced.
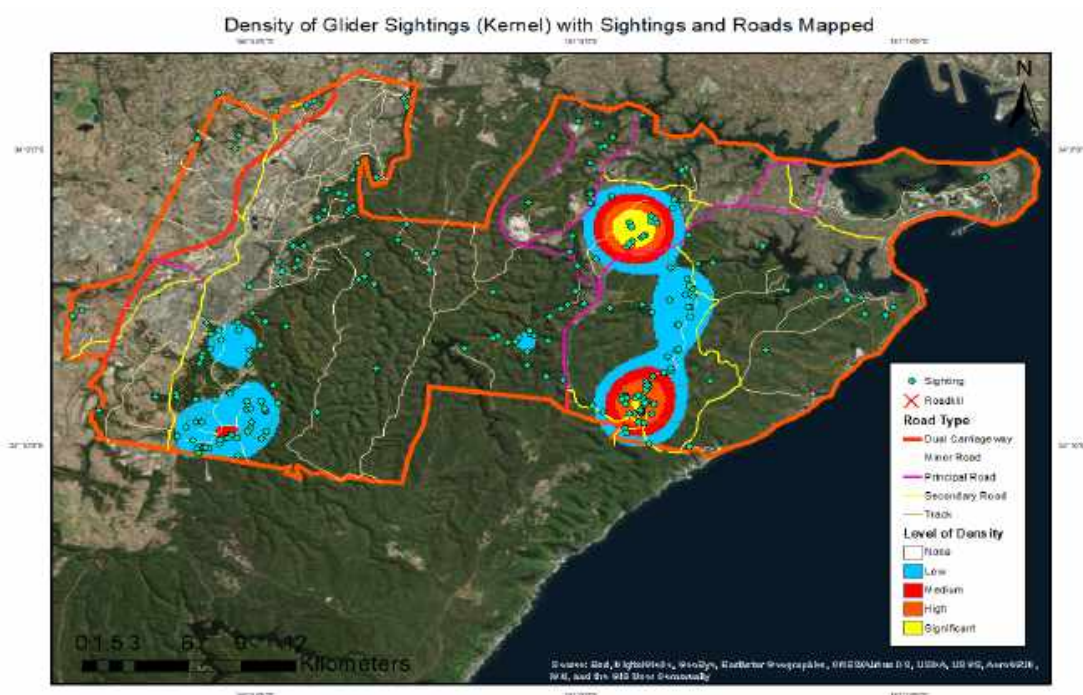
Figure 20: Glider hotspots using Kernel Density with sightings and roads mapped

The above figure shows that the majority of glider sightings occur within national park areas along tracks or minor roads. The only glider roadkill that was found within this study also occurred in the northernmost hotspot.

4.3 Cost surface

Using the reclassified datasets as seen in **Appendix 1** through **Appendix 5**, the following cost surface of the study area was generated:
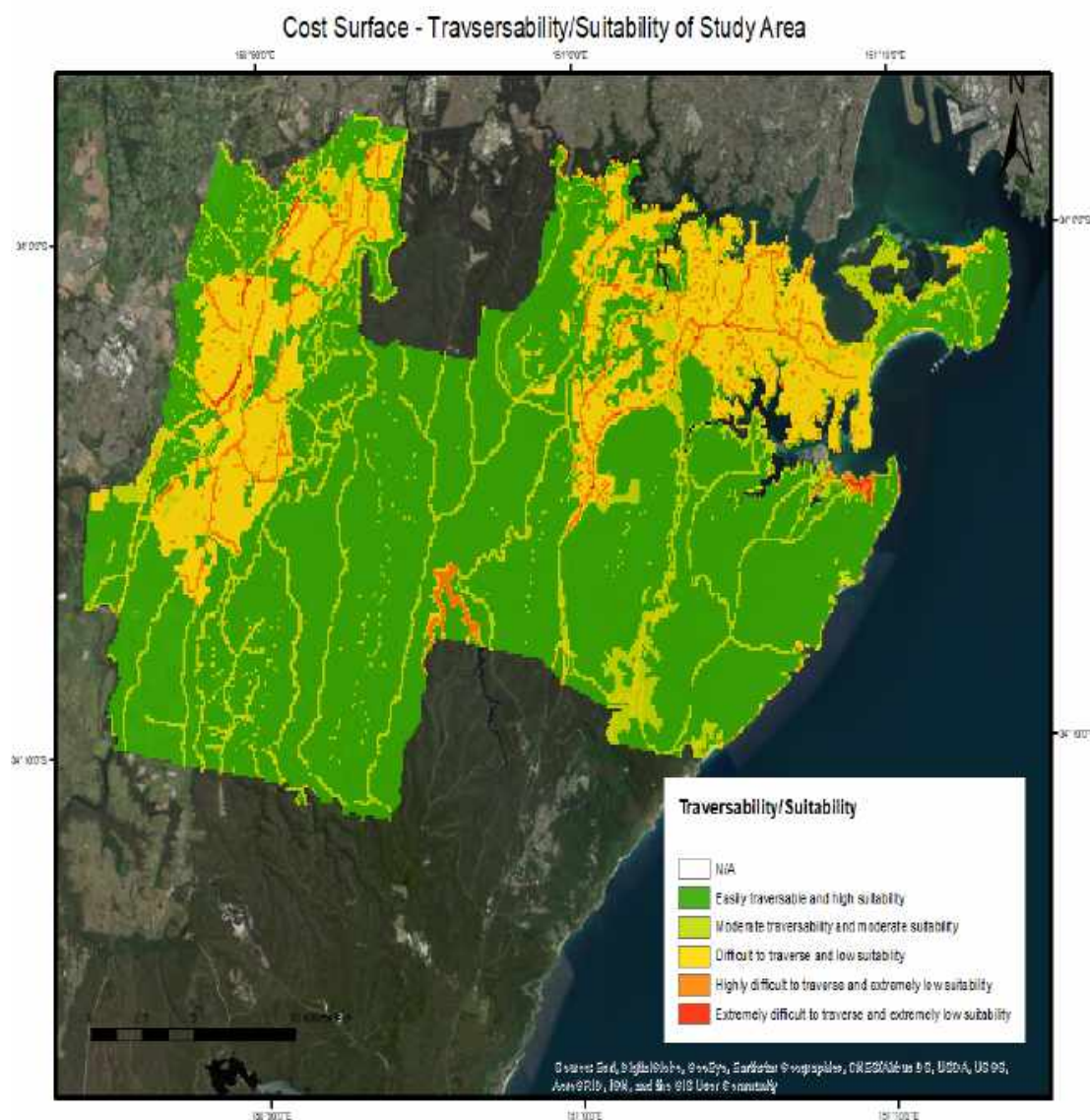
Figure 21: Output of the basic cost surface showing suitability and traversability of the study area.

Values in the final output ranged from 6 to 54. Values of 6, the lowest possible value, only occurred in areas where there was ocean and thus was assigned the category of N/A on the map. The remaining five classes were classified using natural breaks of values from 7 to 54:

Easily traversable and high suitability (7-12):

The most suitable and traversable class, shown in green on the map, consisted of areas of predominantly intact mature forest of a suitable native vegetation type. Much of the vegetation in this class is dry sclerophyll forest and the regions on the map may display possible existing habitat corridors.

Moderate traversability and moderate suitability (12-21):

Displayed as a lighter green on the map, this class highlights slightly more unsuitable or less traversable features located amongst suitable vegetation areas. The areas present within this class can be said to be barriers to animal movement, which includes features such as unsuitable vegetation types neighbouring a preferred vegetation type, less significant roads, minor watercourses and areas of greater slope. For this analysis, areas that fall within this class are seen as the barriers to movement and, as such, are the focus areas.

Difficult to traverse and low suitability (21-30):

Features classified within this class, shown in yellow on the map, mainly encompassed residential and built-up features within the study area. Residential areas are not impossible to traverse but do present limitations in terms of species movement and are not suitable.

Highly difficult to traverse and extremely low suitability (30-40) and extremely difficult to traverse and extremely low suitability (40-54):

The two highest classes in this analysis, shown in orange and red, are areas that were deemed to be highly difficult to traverse and had minimal suitability for species. It can hence be said that these areas may be detrimental to species presence. Due to the analysis method which involved adding several raster datasets, areas that were present in these classes often involved one highly weighted feature overlapping another highly weighted feature. For example, in the built-up area to the northwest of the study area (the area in yellow), the observable orange and red features within this area are major, principal and secondary roads as well as a dual carriageway (major highway) that pass through the built-up area. Other features within this class included roads to the northeast of the study area and Woronora dam.

4.4 Discussion of data, spatial analysis and limitations

4.4.1 Data

One point to note between the data of koalas and marsupial gliders is the differences in sighting locations. As seen in *Figure 10*, koala sightings are predominantly located along the edge between mature forest and developed land that is separated by road. Contrary to this, marsupial gliders are predominantly located in close proximity to tracks or minor roads located within the national parks (*Figure 20*). This gives rise to a possible bias problem within this data. As the BioNet Atlas is a publicly accessible repository for sightings that functions from professional and public sightings submission or "citizen science", this may present some bias. This was highlighted within a 2012 AMBS report in which several reasons for data bias were outlined:

- Firstly, there is a bias within the koala records due to a statutory requirement to carry out site surveys before harvesting;
- Secondly, due to citizen science, there is a bias towards sightings on or around roadways due to a greater number of people being able to observe the animals when they travel on roads; and
- Thirdly, there is a bias against records of sightings on private lands due to access restrictions. As well as this, records on public land estate are also sparse.

Another issue within the BioNet Atlas data was the number of animals observed in each sighting. While the number of animals observed in each sighting was recorded in the original data, some grids were left blank while others used a plus symbol to suggest that there may have been more animals than the recorded number. For the purpose of this study, each sighting that did not have a value in the original data was presumed to be only one animal and those that had a plus symbol were presumed to be the minimum value that was recorded.

The lack of data was also an issue present within this study. Fieldwork was beyond the scope and timeframe of this study and, therefore, existing data was used. The NSW BioNet Atlas contained data that could be downloaded, but the biases present in this data due to citizen science are evident. Several organisations were contacted throughout this study with mixed responses. Data was supplied from the Australian

Wildlife Information, Rescue and Education Service (WIRES) for this study; however, data that was recorded by WIRES lacked coordinates for the sighting and, as such, could not be utilised for this study. NSW Roads were contacted and responded via email correspondence, stating that three koalas were killed on Heathcote Road in over a 3-year period. NSW Roads also stated that the only animal-vehicle collisions they record are for those when a tow truck is required to move a vehicle away. New South Wales Roads and Maritime Services and Holsworthy Barracks were also contacted but did not respond.

4.4.2 Hotspot analysis

Hotspot analysis proved to be an effective way to show where significant spatial clustering of animals occurred. For the koala dataset, several hotspots were found when analysing the whole dataset. Out of the 23 roadkills that were recorded, 12 of these roadkills occurred along a 3.8km stretch of Appin Road, in which 10 of these roadkills coincided with the hotspots of the whole dataset. Two small hotspots were found using the Point Density tool for the glider dataset, but when this dataset was analysed using the Kernel Density tool, two much larger hotspots were observed along with a smaller third hotspot.

The differences between the Point Density and Kernel Density tools within ArcMap were prevalent within this study, with Point Density showing more defined areas of clustering within a larger dataset, but producing a significantly less clustered map in a smaller dataset. Thus, within the smaller glider dataset, the Kernel Density tool was used to enhance the size of the two observed Point Density clusters while also connecting these two clusters through smooth shading and generating another cluster.

Through the use of these tools, however, some anomalies can be observed. With a large disparity between koala sighting locations between the Campbelltown and Sutherland local government areas (Campbelltown = 1,288; Sutherland = 154), some expected dense areas do not show up from this analysis. This is present in the northwest region of Sutherland where a large cluster of koala sighting locations are observed towards the

north of Heathcote Road. However, due to the distance away from the majority of the koala sightings, this possible hotspot does not show up using this analysis method.

Although roadkill hotspot analyses can be used as a general indicator of habitat-roadkill associations, they should not be the sole indicator of the best location for installing mitigation structures (Lesbarrerès & Fahrig, 2012; Eberhardt et al., 2013). The most common method for the determination of hotspots is a regular survey of carcasses or sightings that are geo-referenced and segmented from which hotspots can then be identified (Eberhardt et al., 2013; Santos et al., 2015). According to Santos et al. (2015) however, this method of hotspot identification has major problems, such as imperfect detection due to a failure to detect carcasses, as well as carcass persistence being an issue due to decomposition, scavengers and other vehicles.

This point of imperfect detection is especially prevalent within the glider dataset. While koalas are a physically large species whereby koalas struck by vehicles can be easily observed on a road, the smallest glider species, feathertail gliders, weigh a maximum of 15g. Similarly, the most common glider species in the study area, sugar gliders, weigh a maximum of 130g (Lindenmayer, 1997). If a glider were to be struck by a vehicle, the driver of the vehicle may not notice that they have hit a glider. Furthermore, due to the small size of gliders, the bodies of gliders that are hit by a vehicle and end up on a road may quickly disappear due to further vehicular traffic and quicker decomposition times. Hence, it can be said that the glider data used may underrepresent actual roadkill numbers.

Upon conducting hotspot analysis in the koala dataset, an area of interest was observed on a 3.8km section of Appin Road. From this analysis, it could be seen that koalas were killed on this section of Appin Road that separated relatively intact dry sclerophyll forest to the east, heavily fragmented remnant habitat patches amongst pastoral land to the west and a built-up area to the north. Due to this type of analysis it cannot be determined whether or not the species observed either side of Appin Road are functionally connected. The koalas observed could potentially be a larger koala community separated into smaller subpopulations due to habitat fragmentation and be disconnected by this road, or could be completely genetically isolated from one another.

Hence it is difficult to determine if the road is a barrier between subpopulations and a limiting factor to their movement without genetic studies.

Due to the small number of roadkills recorded in both the koala and glider datasets, hotspots of animal-vehicle collisions could not be produced in an effective manner. Animal roadkills in small datasets would show no significant visual and numerical output from this analysis and thus would be redundant as the hotspots would occur in all of the expected areas. Analysis of whole datasets for this study proved to be a much better method for showing areas of high species presence – and although the hotspots from the sighting locations lined up well with the roadkill locations, it is not an entirely accurate depiction of where animal-vehicle collisions are occurring. More thorough monitoring programs to find roadkill hotspots have been conducted – for example, Ramp et al. (2005) monitored a 40km segment of the Snowy Mountain Highway, observing over 4,000 animals killed by vehicles over a 4-year period.

4.4.3 Cost surface

The creation of a basic cost surface using reclassified raster data layers proved to be a simple yet effective way to generate a suitability/traversability index within the study area. From the output, areas in green represent relatively intact mature forest that are potentially habitat corridors for species movement. Areas shown as light green in the map offer barriers to species movement, which includes roads, waterways, steep slopes and/or unsuitable habitat. The areas of concern found within the hotspot analysis for koalas on Appin Road shows that this road is a barrier to species movement. For the glider dataset, many of the glider sightings occurred within national parks and while the tracks and minor roads present in these areas would be a barrier to movement, the influence may not be as significant as other road types.

However, while this method did fulfil its intended purposes, some shortcomings from this form of analysis do exist. The first issue that arises is the subjectivity of the reclassification process when assigning values to the various raster datasets. For example, a watercourse layer was not weighted as highly as a road as it was not the focus of this study. Major and minor streams may have a profound influence on species

movement, possibly as much—if not greater—than roads or habitat type/land use which were the centre of this study – but as they are not the focus of the study, they were not given as much weight. The effect of data layers, such as slope, in this study were also difficult to assign a value to due to the lack of literature that exists for the influence of slope on the selected species.

Another issue present is the use of incomplete datasets for the basic cost surface analysis. While the datasets used did cover the majority of the spatial extent of the study area, some areas were restricted by a lack of data. This was especially apparent for the area surrounding the segment of Appin Road. No dataset was publicly available that mapped the neighbouring pastoral land around this road. As such, some sections of the pastoral land were classified as grasslands within the native vegetation layer but significant areas of this land remained unclassified. This resulted in these areas being classified as a null value and meant it was given less weight in the final output and was not accurately represented.

The collation of better datasets to encapsulate every aspect of the landscape, as well as different reclassification methods, the addition of more datasets and the use of more in-depth tools could better represent the study area.

4.5 General discussion of mitigation structures

A range of factors need to be considered when evaluating the type of and location for a mitigation structure. Shaw (2003, as cited in Magnus et al., (2004)) emphasized the need for information about why and where roadkills are occurring so that roadkill mitigation can be addressed at the planning stage of road construction. This would enable mitigation measures to be less expensive and more effective. With information from hotspot analyses and habitat suitability available through spatial analysis of data, the perceived effectiveness of the proposed mitigation structure then needs to be reviewed. One such approach by Thompson & Lanham (2014) utilised a multi-criteria system for ranking short-term and long-term mitigation options. For each mitigation structure, a score was assigned to three criterion: environmental, social/cultural and financial impact. In each of these criteria, the impact on species and ease of implementation were also assessed. Scores for these ranged from -5 (high negative

impact and a very low chance of implementation) to +5 (high positive impact and a very high chance of implementation).

Other methods for selecting an appropriate mitigation measures have also been proposed. In a paper by Rytwinski et al. (2015), seven key questions that road planners commonly have about mitigation structures were highlighted. The answers to these questions remain largely unanswered within literature, yet these questions are essential so that resources for road mitigation are allocated in the most effective manner and will ultimately have the desired effect. The seven questions from Rytwinski et al. (2015) are as follows:

- Question 1: Does a given crossing structure work? What type and size (width, height, length) of crossing structure should we use?
- Question 2: How many crossing structures should we build?
- Question 3: Is it more effective to install a small number of large-sized crossing structures or a large number of small-sized crossing structures?
- Question 4: How much barrier fencing is needed for a given length of road?
- Question 5: Do we need funnel fencing to lead animals to crossing structures and how long does such fencing have to be?
- Question 6: How should we manage/manipulate the environment in the area around the crossing structures and fencing?
- Question 7: Where should we place crossing structures and barrier fencing?

Some of the above questions can be easily answered after conducting a literature review. To answer Question 1, it is essential to know the type of structure to install for your target species. From the literature review within this paper, marsupial gliders predominantly use glider poles, rope-bridges and occasionally culverts, whereas koalas use a range of crossing structures such as underpasses, culverts and land-bridges. For Questions 4 and 5, exclusion and funnel fencing are seen as an integral part of mitigation structures—often more important that the actual crossing structure—and from the literature review, fencing needs to run the length of the road. Question 6 can also be answered, with studies showing the importance of a smooth transition from the surrounding environment onto the crossing structure. This can be done by revegetation at the crossing structure entry (e.g. Dexter et al., 2016) or through the use of other structures, such as wildlife railings in culverts (e.g. Goldingay et al., 2018), to transition

from the surrounding habitat onto the crossing structure. Similarly, Question 7 can be answered by carrying out spatial analysis to find hotspots of high species presence or areas where roadkills are occurring. The remaining questions, Question 2 and 3 however, are areas for conjecture within the literature and seem to be highly dependent on biotic and abiotic factors in the proposed area.

While the proposed effectiveness of a crossing structure is essential in determining the possible feasibility, it is also vital to uncover the potential costs of a structure. Cost and financial considerations are one of the most important factors that must be accounted for when planning or building a crossing structure – and due to the cost of these structures is it of utmost importance to maximise cost effectiveness (Polak et al., 2014). Crossing structures that are installed on a road when the road is built cost significantly less than structures that are retrofitted onto a road (Taylor & Goldingay, 2012). Underpasses are much more common than overpasses, and overpasses are also significantly more expensive and provide the most challenges in terms of installation and management (Jones, 2010).

The target species in a study will have a major influence on the potential costs. Marsupial gliders show a preference to using glider poles and rope-bridges, two of the cheapest mitigation measures. Glider poles, especially, are an incredibly cost effective structure, with a study by Ball & Goldingay (2008) quoting the delivery and installation of five glider poles cost $1,945 per pole. Glider poles are very cheap to install, require minimal maintenance and cause little to no disruption to the surrounding habitat, making them a cheap yet effective mitigation structure for marsupial gliders (Ball & Goldingay, 2008). Contrary to this, koalas within the literature review of this study were found to use underpasses, culverts and land-bridge overpasses – amongst the most expensive mitigation structures. In a study by Dexter et al. (2016) involving retrofitted mitigation structures, fauna exclusion fencing cost $180/m, construction work on the underpass cost $500,000, weed control and vegetation rehabilitation cost approximately $25,000 at each of the six sites, and the construction of a "dry ledge" walkway in an underpass at one site cost $100,000.

Although these structures will need an upfront cost for construction and installation, other costs for upkeep, maintenance and upgrades are also significant. Mitigation measures should be designed to last long-term—that is, the life of the road—and materials for construction need to be enduring (Baxter-Gilbert et al., 2015). Cost-benefit analyses are routinely done to determine if potential success of a mitigation structure outweighs the monetary expenditure to install the structure (e.g. Huijser et al., 2009). For species that show minimal preference to one specific crossing structure, such as koalas, it may be beneficial to study other species in the area to maximise cost effectiveness if a structure were to be installed.

Instead of installing a crossing structure along with exclusion fencing, the choice may be made to solely install exclusion fencing. This alternative is not cheap and requires decisions over height and distance, as well as ongoing maintenance costs for a structure that could very well further divide a wildlife community that is separated by a road. The maintenance on exclusion fencing is ongoing and any damage to these structures can cause an increase in wildlife-vehicle collisions.

5. Recommendations for future research

This study provides a solid foundation for further research by using basic spatial analysis to show areas of concern, by way of hotspots and potential interruptions to existing habitat corridors, and a literature review to emphasize preferred crossing structures for the target species and the knowledge gaps that exist within the literature.

Due to the simplicity of the spatial analysis methodology used, more in-depth spatial analysis techniques could be utilised to further assess areas of concern. Below are examples of other spatial analysis techniques that could be used:

- Other spatial analysis tools within GIS software and/or the use of statistics to further determine hotspots. One such study by Santos et al. (2015) used statistics to uncover "true" and "false" hotspots within data.
- Habitat mapping for specific species, similar to the methods used by Lunney et al. (2000) or Callaghan et al. (2011).

- More features within the cost surface analysis. Ahmad et al. (2018) used environmental factors along with disturbance factors to map habitat suitability.
- The use of buffers around road edges where no habitat is present (Ahmad et al., 2018)
- The use of a non-native vegetation layer and more refined land use datasets to better depict the landscape.

More influence can also be given to roads. Within this study, the only road features that were looked at were the road classification and a brief look at traffic volume. A study by Valero et al. (2015) conducted a hotspot analysis of road segments and found that daily traffic volume, width of road, speed limit and number of lanes affect whether a particular road segment has a high or low number of wildlife-vehicle collisions. High wildlife-vehicle collisions zones were found to have wider lanes, a wider roadside shoulder and gentler slopes, whereas narrow roads and roads with minimal curvature were majorly influenced by driver visibility and speed. Assessments similar to this could be conducted in the study area.

Management strategies and legislation have been widely implemented for species. During the writing of this paper, the New South Wales Koala Strategy for 2018 (NSW Government, 2018) was released, which highlighted 24,000ha of new koala reserves and parks. Other features of this Koala Strategy included fixing priority roadkill hotspots, increasing monitoring, establishing a new single wildlife rescue call number and the creation of a koala information base. While the creation of wildlife reserves are necessary, Lunney et al. (2000) noted that although national parks and nature reserves in New South Wales support koalas, the majority of koalas exist outside of these areas. Thus, there is an essential need for citizen science to establish population numbers and location.

The success of citizen science has been widely acknowledged within literature (e.g. Harris & Goldingay, 2003; Predavec et al., 2018). Previous citizen science studies have been conducted on koalas in the Sutherland Shire and Campbelltown regions (Ward, 2002), with information being sourced from the public via postal surveys and with the contribution of volunteers and various organisations. The NSW BioNet Atlas is the most complete compiled dataset for wildlife sightings for this region, although there is a high

possibility that many people are unaware of this database. Promoting the use and exposing people to the BioNet Atlas would cause an increase in the number of sightings on records. Independent surveys or online polls for daily travellers on roads within this area are other potential options.

Monitoring of species is also a potential method that can be utilised. By using an approach similar to Lassau et al. (2008), species home ranges within a specific study area could be better understood. If monitoring programs were to be done however, they must be conducted as ethically as possible and in a manner that will not harm the animals.

Due to the scope of this study, it is impossible to determine if the roads present in the study area and dividing wildlife communities into smaller subpopulations. Therefore, genetic studies to determine whether or not animals on either side of a road are genetically linked could be conducted. Genetic studies using a methodology similar to Soanes et al. (2013) may provide insight into communities affected by roads and place more emphasis on these certain areas.

6. Conclusion

The koalas and marsupial gliders present in the Sutherland Shire and Campbelltown regions of New South Wales, Australia are potentially at risk to the effects of roads, habitat fragmentation and habitat loss. As these species are arboreal and require a canopy layer to traverse through their home range, the loss of essential habitat may present various challenges for these highly specialised species. Mitigation measures, such as wildlife crossing structures, are identified as one of the best methods to offset the impacts of roads, habitat fragmentation and habitat loss.

Numerous studies have been conducted to study crossing structures. Within the literature, koalas show a preference to using culverts and land-bridge overpasses, whereas marsupial gliders prefer to use glider poles and rope-bridges. Although studies of these structures do provide insight into species use, the criteria for determining whether or not these structures are successful is not universal.

The use of basic spatial analysis techniques to study trends within BioNet Atlas data for koalas and marsupial gliders proved to be effective. Although the methods used to determine hotspots of species presence and areas that were unsuitable and/or difficult to traverse achieved their intended purpose, issues with data biases and incomplete datasets limited the accuracy of analysis techniques.

Overall, more in-depth spatial analysis techniques must be used to ascertain areas where heavily fragmented habitat and roads present barriers to species movement. A range of criteria must also be assessed to determine if a crossing structure should be placed at a specific location. It is suggested that the use of more complete datasets, and the potential for increased citizen science and monitoring in the area should be utilised.

References

Adams-Hosking, C., McBride, M.F., Baxter, G., Burgman, M., de Villiers, D., Kavanagh, R., Lawler, I., Lunney, D., Melzer, A., Menkhorst, P., Molsher, R., Moore, B.D., Phalen, D., Rhodes, J.R., Todd, C., Whisson, D., McApline, C.A. (2016). Use of expert knowledge to elicit population trends for the koala (Phascolarctos cinerus). *Diversity and Distributions*, **22**(3), pp. 249-262.

Ahmad, F., Goparaju, L. & Qayum, A. (2018). Wild life habitat suitability and conservation hotspot mapping: Remote Sensing and GIS based decision support system. *AIMS Geosciences*, **4**(1), pp. 66-87.

AMBS (2012). Investigation of the Impact of Roads on Koalas: Final Report. Prepared by Australian Museum Business Services for the NSW Roads and Maritime Services.

Andrén, H. (1994). Effects of Habitat Fragmentation on Birds and Mammals in Landscapes with Different Proportions of Suitable Habitat: A Review. *Oikos*, **71**(3), pp. 355-366.

Andrews, A. (1990). Fragmentation of Habitat by Roas and Utility Corridors: A Review. *Australian Zoologist*, **26**(3), pp. 130-141.

Ascensão, F., Clevenger, A., Santos-Reis, M., Urbano, P. & Jackson, N. (2013). Wildlife-vehicle collision mitigation: Is partial fencing the answer? An Agent-based model approach. *Ecological modelling*, **257**, pp. 36-43.

Ball, T.M. & Goldingay, R.L. (2008). Can wooden poles be used to reconnect habitat for a gliding mammal? *Landscape and Urban Planning*, **87**(2), pp. 140-146.

Baxter-Gilbert, J.H., Riley, J.L., Lesbarrères, D., Litzgus, J.D. & Moreno-Rueda, G. (2015). Mitigating Reptile Road Mortalilty: Fence Failures Compromise Ecopassage Effectiveness. *PLoS ONE*, **10**(3), pp. 1-15.

BITRE (2015). Key Australian infrastructure statistics 2015. *Department of Infrstructure and Regional Development: Bureau of Infrastructure, Transports and Regional Economics.*

Bennett, A.F. (1991). Roads, roadsides and wildlife conservation: a review. *In Nature Conservation 2: The Role of Corridors* ed Saunders D.A. and Hobbs R.J., Surrey Beatty, Chipping Norton, NSW.

Bennett, A.F. (1999). Linkages in the Landscape: The Role of Corridors and Connectivity in Wildlife Conservation. *IUCN – The World Conservation Union.*

Bolger, D.T., Alberts, A.C., Sauvajot, R.M., Potenza, P., McAlvin, C. Tran, D., Mazzoni, S. & Soule, M.E. (1997). Response of Rodents to Habitat Fragmentation in Coastal Southern California. *Ecological Application*, **7**(2), pp. 552-563.

Bond, A.R. & Jones, D.N. (2008). Temporal trends in use of fauna-friendly underpasses and overpasses. *Wildlife Research*, **35**, pp. 103-112.

Callaghan, J., McAlpine, C., Mitchell, D., Thompson, J., Bowen, M., Rhodes, J., de Jong, C., Domalewski, R. & Scott, A. (2011). Ranking and mapping koala habitat quality for conservation planning on the basis of indirect evidence of tree-species use: a case study of Noosa Shire, south-eastern Queensland. *Wildlife Research,* **38**, pp. 89-102.

Carly, F.M., Thomson, K. & van der Ree, R. (2013). Permeability of the urban matrix to arboreal gliding mammals: Sugar gliders in Melbourne, Australia. *Austral Ecology,* **38**, pp. 609-616.

Conrad, E. (2014). The Economic Value of the Koala. *Australian Koala Foundation*.

Corlatti, L., Hackländer, K. & Frey-Roos, F. (2008). Ability of Wildlife Overpasses to Provide Connectivity and Prevent Genetic Isolation. *Conservation Biology,* **23**(3), pp. 548-556.

Cunnington, G.M., Garrah, E., Eberhardt, E. & Fahrig, L. (2014). Culverts alone do not reduce road mortality in anurans. *Ecoscience*, **21**(1), pp. 69-78.

de Villiers, D. (1999). Koala Management in SE Queensland – How do we know it works? In *Proceedings of the Conference on the Status of the Koala in 1999*. Australian Koala Foundation, Brisbane.

DECC (2008). Recovery plan for the koala (Phascolarctos cinerus). Department of Environment & Climate Change, Sydney, NSW.

DECCW (2011). The Vertebrate Fauna of Royal & Heathcote National Parks and Garawarra State Conservation Area. *New South Wales Department of Environment, Climate Change & Water.*

Dennison, S., Frankham, G.J., Neaves, L.E., Flanagan, C., FitzGibbon, S., Eldridge, M.B.D. & Johnson, R.N. (2016). Population genetics of the koala (Phascolarctos cinereus) in north-eastern New South Wales and south-eastern Queensland. *Australian Journal of Zoology*, **64**(6), pp. 402-412.

Dexter, C.E., Appelby, R.G., Edgar, J.P., Scott, J. & Jones, D.N. (2016). Using complementary remote detection methods for retrofitted eco-passages: a case study for monitoring individual koalas in south-east Queensland. *Wildlife Research*, **43**, pp. 369-379.

Dexter, C.E., Appleby, R.G., Scott, J., Edgar, J.P. & Jones, N.D. (2017). Individuals matter: predicting koala road crossing behaviour in south-east Queensland. *Australian Mammalogy*, **40**(1), pp. 67-75.

Diaz-Varela, E.R., Vazquez-Gonzalez, I., Marey-Pérez, M.F. & Álvarez-López, C.J. (2011). Assessing methods of mitigation wildlife-vehicle collisions by accident characterization and spatial analysis. *Transport Research Part D*, **16**, pp. 281-287.

Dique, D.S., Thompson, J., Preece, H.J., Penfold, G.C., de Villiers, D.L. & Leslie, R.S. (2003). Koala mortality on roads in south-east Queensland: the koala speed-zone trial. *Wildlife Research*, **30**, pp. 419-426.

Dobson, M., Goldingay, R.L. & Sharpe, D.J. (2005). Feeding behaviour of the squirrel glider in remnant habitat in Brisbane. *Australian Mammalogy,* **27**, pp. 27-35.

Dougherty, R.R. (2015). Hotspot Analysis of Wildlife Vehicle Collisions of BR-262 Mato Grosso Do Sul, Brazil and Recommendations for Mitigation Efforts. *MSc thesis, Florida Atlantic University, Boca Raton*.

Eberhardt, E., Mitchell, S. &Fahrig, L. (2013). Road kill hotspots do not effectively indicate mitigation locations when past road kill has depressed populations: Roadkill Hotspots Can Mislead Mitigation. *The Journal of Wildlife Management*, **77**(7), pp. 1353-1359.

Fahrig, L. (2003). Effects of habitat fragmentation on biodiversity. *Annual Review of Ecology, Evolution, and Systematics*, **34**(1), pp. 487-515.

Fowler, E.V., Houlden, B.A., Hoeben, P. & Timms, P. (2000). Genetic diversity and gene flow among southeastern Queensland koalas (Phascolarctos cinerus. *Molecular Ecology*, **9**, pp. 155-164.

Forman, R.T.T. & Alexander, L.E. (1998). Roads and their major ecological effects. *Annual Review of Ecology and Systematics*, **29**, pp. 207-231.

Forman, R.T.T., Sperling, D., Bissonette, J.A., Clevenger, A.P., Cutshall, C.D., Dale, V.H., Fahrig, L., France, R.L., Goldman, C.R., Heanue, K., Jones, J.A., Swanson, F.J., Turrentine, T. & Winter, T.C. (2003). *Road Ecology: Science and Solutions*. Island Press, Washington.

Glista, D.J., DeVault, T.L. & DeWoody, J.A. (2009). A review of mitigation measures for reducing wildlife mortality on roadways. *Landscape and Urban Planning*, **91**, pp. 1-7.

Goldingay, R.L. & Whelan, R.J. (1997). Powerline Easements: Do They Promote Edge Effects in Eucalypt Forest for Small Mammals? *Wildlife Research*, **24**(6), pp. 737-744.

Goldingay, R.L., Taylor, B.D. & Ball, T. (2011). Wooden poles can provide habitat connectivity for a gliding mammal. *Australian Mammology*, **33**(1), pp. 36-43.

Goldingay, R.L., Rohweder, D. & Taylor, B.D. (2013). Will arboreal mammals use rope-bridges across a highway in eastern Australia? *Australian Mammalogy*, **35**(1), pp. 30-38.

Goldingay, R.L., Taylor, A.C., Ball, T.M., Sharpe, D.J. et al. (2013). Fine-Scale Genetic Response to Landscape Change in a Gliding Mammal. *PLoS ONE*, **8**(12), pp. 1-10.

Goldingay, R.L. (2014). Gliding performance in the yellow-bellied glider in low-canopy forest. *Australia Mammalogy*, **36**, pp. 254-258.

Goldingay, R.L. & Dobner, B. (2014). Home range areas of koalas in an urban area of north-east New South Wales. *Australia Mammalogy*, **36**(1), pp. 74-80.

Goldingay, R.L. & Taylor, B.D. (2017). Targeted field testing of wildlife road-crossing structures: koalas and canopy rope-bridges. *Australian Mammalogy*, **39**, pp. 100-104.

Goldingay, R.L., Taylor, B.D. & Parkyn, J.L. (2018). Movement of small mammals through a road-underpass is facilitated by a wildlife railing. *Unpublished paper.*

Harris, J.M. & Goldingay, R.L. (2003). A community-based survey of the Koala Phascolarctos cinerus in the Lismore region of North-eastern New South Wales. *Australian Mammalogy*, **25**, pp. 155-167.

Hartigan, J.A. (1975). Clustering Algorithms. *John Wiley & Sons, Hoboken, New Jersey.*

Hedlund, J.H., Curtis, P.D., Curtis, G. & Williams, A.F. (2004). Methods to Reduce Traffic Crashes Involving Deer: What Works and What Does Not. *Traffic Injury Prevention,* **5**(2), pp. 122-131.

Huijser, M.P., Duffield, J.W., Clevenger, A.P., Ament, R.J. & McGowen, P.T. (2009). Cost-Benefit Analyses of Mitigation Measures Aimed at Reducing Collisions with Large Undulates in the United States and Canada: a Decision Support Tool. *Ecology and Society,* **14**(2),

Huijser, M.P., Fairbank, E.R., Camel-Means, W., Graham, J., Watson, V., Basting, P. & Becker, D. (2016). Effectivness of short sections of wildlife fencing and crossing structures along highways in reducing wildlife-vehicles collisions and providing safe crossing opportunities for large mammals. *Biological Conservation*, **197**, pp. 61-68.

Hundloe, T. & Hamilton, C. (1997). Koalas and Tourism: An Economic Evaluation (Issue 13 of Discussion Paper). *The Australia Institute*.

Jones, D. (2010). Vegetation structure on overpasses is critical in overcoming the road barrier effect for small birds. *Unpublished paper.*

Jones, D.N., Bakker, M., Bicket, O., Coutts, R. & Wearing, T. (2011). Restoring habitat connectivity over the road: vegetation on a fauna land-bridge in south-east Queensland. *Ecological Management & Restoration*, **12**(1), pp. 76-79.

Kintsch, J. & Cramer, P.C. (2011). Permeability of Existing Structures for Terrestrial Wildlife: A Passage Assessment System. Research report for *Washington State Department of Transport,* Olympia, WA.

Krisp, J.M. & Durot, S. (2007). Segmentation of lines based on point densities—An optimisation of wildlife warning sign placement in southern Finland. *Accident Analysis & Prevention*, **39**, pp. 38-46.

Lassau, S.A., Ryan, B., Close, R., Moon, C., Geraghty, P., Coyle, A. & Pile, J. (2008). Home ranges and mortality of a roadside Koala Phascolarctos cinerus population at Bonville,

New South Wales. *Australian Zoologist*, pp. 127-136 in *Too close for comfort: contentious issues in human-wildlife encounters*, edited by Lunney, D., Munn, A. & Meikle, W., Royal Zoological Society of New South Wales, Mosman, NSW, Australia.

Lawson, A.B. (2010). Hotspot detection and clustering: ways and means. *Environmental and Ecological Statistics*, **17**, pp. 231-245.

Lee, K.E., Seddon, J.M., Corley, S.W., Ellis, W.A.H., Johnston, S.D., de Villiers, D.L., Preece, H.J. & Carrick, F.N. (2009). Genetic variation and structuring in the threatened koala populations of Southeast Queensland. *Conservation Genetics,* **11**(6).

Lesbarrerès, D. & Fahrig, L. (2012). Measures to reduce population fragmentation by roads: what has worked and how do we know? *Trends in Ecology and Evolution,* **27**(7), pp. 374-380.

Lindenmayer D.B. (1997). Differences in the biology and ecology of arboreal marsupials in forests of southeastern Australia. *Journal of Mammalogy,* **78**(4), pp. 1117-1127.

Lindenmayer, D.B., Cunningham, R.B., Pope, M.L. & Donnely, C.F. (1999). The Response of Arboreal Marsupials to Landscape Context: A Large-Scale Fragmentation Study. *Ecological Applications*, **9**(2), 594-611.

Little, S.J., Harcourt, R.G., Clevenger, A.P. (2002). Do wildlife passages act as prey-traps? *Biological Conservation*, **107**, pp. 135-145.

Lunney, D., Matthews, A., Moon, C. & Ferrer, S. (2000). Incorporating Habitat Mapping into Practical Koala Conservation on Private Lands. *Conservation Biology,* **14**(3), pp. 669-680.

Magnus, Z., Kriwoken, L.K., Mooney, N.J. & Jones, M.E. (2004). Reducing the incidence of wildlife roadkill: improving the visitor experience in Tasmania. *Cooperative Research Centre for Sustainable Tourism (CRCST).*

Mata, C., Hervás, I., Herranz, J., Suárez, F. & Malo, J.E. (2005). Complementary use by vertebrates of crossing structures along a fenced Spanish motorway. *Biological Conservation*, **124**(3), pp. 397-405.

Mata, C., Hervás, I., Herranz, J., Suárez, F. & Malo, J.E. (2008). Are motorway wildlife passages worth building? Vertebrate use of road-crossing structures on a Spanish morotway. *Journal of Environmental Management*, **88**(3), pp. 407-415.

Mata, C., Hervás, I., Herranz, J. Malo, J.E. & Suárez, F. (2009). Seasonal changes in wildlife use of motorway crossing structures and their impliaion for monitoring programmes. *Transport Research Part D*, **14**(7), pp. 447-452.

Morelle, K., Lehaire, F. & Lejeune, P. (2013). Spatio-temporal patterns of wildlife-vehicle collisions in a region with high-density road network. *Nature Conservation*, **5**, pp. 53-73.

Moshtagie, M. & Kaboli, M. (2015). Finding the best location for installing wildlife signs using kernellt density estimation in Khojir National Park. *International Journal of Environmental Health Engineering*, **4**(3), pp. 1-6.

Nelson, T.A. & Boots, B. (2008). Detection spatial hot spots in landscape ecology. *Ecography*, **5**, pp. 556-566.

NSW Chief Scientist & Engineer (2016). Report of the Independent Review into the Decline of Koala Populations in Key Areas of NSW. *NSW Government.*

NSW Government (2018). NSW Koala Strategy. Published by *Office of Environment and Heritage* on behalf of the *NSW Government, Sydney.*

NSW National Parks and Wildlife Service (2000). Royal National Park, Heathcote National Park and Garawarra Recreation area plan of management. *New South Wales National Parks and Wildlife Service, Sydney, Australia.*

NSW RMS (no date). Bonville Upgrade Fauna Overpass. *A presentation from the New South Wales Roads and Maritime Service.*

NSW RMS (2014). Bonville upgrade – Fauna control measures. *Roads and Maritime Services*, **14.**286, Grafton, NSW, Australia.

NSW RMS (2015). Koala Management Plan Section 1 and 2: Woolgoola to Ballina Pacific Highway Upgrade. *New South Wales Roads and Maritime Services, Sydney, Australia*.

NSW Scientific Committee (2008). Squirrel Glider Petaurus norfolcensis: Review of current information in NSW – August 2008. *Unpublished report arising from the Review of the Schedules of the Threatened Species Conservation Act 1995. NSW Scientific Committee, Hurstville.*

Polak, T., Rhodes, J.R., Jones, D. Possingham, H.P., Jacqueline, F. (2014). Optimal planning for mitigating the impacts of roads on wildlife. *Journal of Applied Ecology*, **51**(3), pp. 726-734.

Possingham, H.P., Lindenmayer, D.B., Norton, T.W. & Davies, I. (1994). Metapopulations viability analysis of the greater glider Petauoides volans in a wood production area. *Biological Conservation,* **70**, pp. 227-236.

Predavec, M., Lunney, D., Shannon, I., Lennon, J., Sonawanem I. & Crowther, M. (2018). Using reperat citizen science surveys of koalas to assess their population trend in the north-west of New South Wales: scale matters. *Australian Mammalogy,* **40**, pp. 47-57.

Preece, H.J. (2007). Identifying hotspots for threats to koalas using spatial analysis. *Proceedings of the MODSIM 2007 international congress on modelling and simulation*, pp. 1294-1300.

Queensland Government (2000). Fauna Sensitive Road Design. *Queensland Government Department of Main Roads. Planning, Design and Environment Division.*

Ramp, D., Caldwell, J., Edwards, K.A., Warton, D. & Croft, D.B. (2005). Modelling of wildlife fatality hotspots along the Snowy Mountain Highway in New South Wales, Australia. *Biological Conservation*, **126**, pp. 474-490.

Ramp, D., Wilson, V.K. & Croft, D.B. (2006). Assessing the impacts of roads in peri-urban reserves: Road-based fatalitied and road usage by wildlife in the Royal National Park, New South Wales, Australia. *Biological Conservation*, **129**(3), pp 348-359.

Reed P.C., Lunney D. and Walker P. (1990). A 1986-1987 survey of the Koala Phascolarctos cinereus (Goldfuss) in New South Wales and an ecological interpretation of its distribution. pp. 55-74 in *Biology of the Koala* ed. A.K. Lee, K.A. Handasyde and G.D. Sanson, Surrey Beatty and Sons, Sydney.

Rhodes, J.R., Callaghan, J.G., McAlpine, C.A., de Jong, C., Bowen, M.E., Mitchell, D.L., Lunney, D. & Possingham, H.P. (2008). Regional variation in habitat-occupancy thresholds: a warning for conservation planning. *Journal of Applied Ecology*, **45**, pp. 549-557.

Rowden, P., Steinhardt, D. & Sheehan, M. (2008). Road crashes involving animals in Australia. *Accident Analysis and Prevention*, **40**, pp. 1865-1871.

Rowand, K.A. (2016). Spatial Patterns of Deer Roadkill in Lucas County, Ohio. *MA Geogprahy thesis, The University of Toledo, Ohio.*

Rowston, C., Catterall, C.P. & Hurst, C. (2002). Habitat preferences of squirrel gliders, Petaurus norfolcensis, in the fragmented landscape of southeast Queensland. *Forest Ecology and Management*, **164**, pp. 197-209.

Rytwinski, T. & Fahrig, L. (2012). Do species life history traits explain population to roads? A meta-analysis. *Biological Conservation*, **147**(1), pp. 87-98.

Rytwinski, T., van der Ree, R., Cunnington, G.M., Fahrig, L., Findlay, C.S., Houlahan, J., Jaeger, J.A.G., Soanes, K. & van der Grift, E.A. (2015). Experimental study designs to improve the evaluation of road mitigation measures for wildlife. *Journal of Environmental Management*, **154**, pp. 48-64.

Santos, S.M., Marques, T.J., Lourenço. A., Medinas, D., Barbosa, A.M., Beja, P. & Mira, A. (2015). Sampling effects on the identification of roadkill hotpsots: Implications for survey design. *Journal of Environmental Management*, **162**, pp. 87-95.

Sarkar, D., Chapman, C.A., Griffin, L. & Sengupta, R. (2014). Analyzing Animal Movement Characteristics From Location Data. *Transactions in GIS*, **19**(4), pp. 516-534.

Sharpe, D.J. & Goldingay, R.L. (2007). Home range of the Australian Squirrel Glider, Petaurus norfolcensis (Diprotondia). *Journal of Mammology*, **88**(6), pp. 1515-1522.

Shaw, R.A. (2003). Predicting the location of wildlife roadkill in Tasmania (In prep).

Siitonen, P., Tanskanen, A. & Lehtinen, A. (2002). Method for Selection of Old-Forest Reserves. *Conservation Biology,* **16**, pp. 1398-1408.

Smith, A.P. (1982). Diet and Feeding Strategies of the Masupial Sugar Glider in Temperate Australia. *Journal of Animal Ecology*, **51**(1), pp. 149-166.

Soanes, K., Carmody Lobo, M., Vesk, P.A., McCarthy, M.A., Moore, J.L. & van der Ree, R. (2013). Movement re-established but not restored: Inferring the effectiveness of road-crossing mitigation for a gliding mammal by monitoring use. *Biological Conservation,* **159**, pp. 434-441.

Soanes, K., Taylor, A.C., Sunnucks, P., Vesk, P.A., Cesarini, S., van der Ree, R. & Wiersma, Y. (2017). Evaluating the success of wildlife crossing structures using genetic approaches and an experimental design: Lessons from a gliding mammal. *Journal of Applied Ecology*, **55**, pp. 129-138.

Taylor, B.D. & Goldingay, R.L. (2003). Cutting the carnage: wildlife usage of road culverts in north-eastern New South Wales. *Wildlife Research*, **30**, pp. 529-537.

Taylor, B.D. & Goldingay, R.L. (2004). Wildlife road-kills on three major roads in north-eastern New South Wales. *Wildlife Research*, **31,** pp 83-91.

Taylor, B.D. & Goldingay, R.L. (2009). Can Road-Crossing Structures Improve Population Viability of an Urban Gliding Mammal? *Ecology and Society*, **14**(2).

Taylor, B.D. (2010). Use and effectiveness of engineered road crossing-structures for wildlife in eastern Australia. *PhD thesis, Griffith University*.

Taylor, B.D. & Goldingay, R.L. (2010). Roads and wildlife: impacts, mitigation and implications for wildlife management in Australia. *Wildlife Research*, **37**, pp. 320-331.

Taylor, A.C., Walker, F.M., Goldingay, R.L., Ball, T., van der Ree, R. & Hayward, M. (2011). Degree of Landscape Fragmenetation Influences Genetic Isolation among Populations of a Gliding Mammal. *PLoS ONE*, **6**(10), pp. e26651.

Taylor, B.D. & Goldingay, R.L. (2012). Restoring Connectivity in Landscapes Fragmented by Major Roads: A Case Study Using Wooden Poles as "Stepping Stones" for Gliding Mammals. *Restoration Ecology*, **20**(6), pp. 671-678.

Taylor, B.D. & Goldingay, R.L. (2013). Squirrel gliders use roadside poles to cross a road gap. *Australian Mammology*, **35**(1), pp. 119-122.

Thompson, C. & Lanham, E. (2014). Reducing roadkill on the Northern beaches: working together for a common goal. A presentation to the *Australasian Network for Ecology and Transportation, July 2014*.

Valero, E., Picos, J. & Álvares, X. (2015). Road and traffic factors correlated to wildlife-vehicle collisions in Galicia, Spain. *Wildlife Research,* **42**(1), pp. 25-34.

Van der Ree, R., Clarkson, D.T., Holland, K., Gulle, N. & Budden, M. (2008). Review of Mitigation Measures used to deal with the Issue of Habitat Fragmentation by Major Linear Infrastructure. *Report for Department of Environment, Water, Heritage and the Arts (DEHWA).*

Ward, S.J. (2002). Koalas and the community: a study of low density populations in southern Sydney. *PhD thesis, University of Western Sydney.*

Wilson, D (2012). Hotspot Analysis of Road Kill in Southern California: a GIS Approach. *MA Geography thesis, California State University, Northridge.*

Appendices

Appendix 1: Map of roads in the study area and table of reclassifications
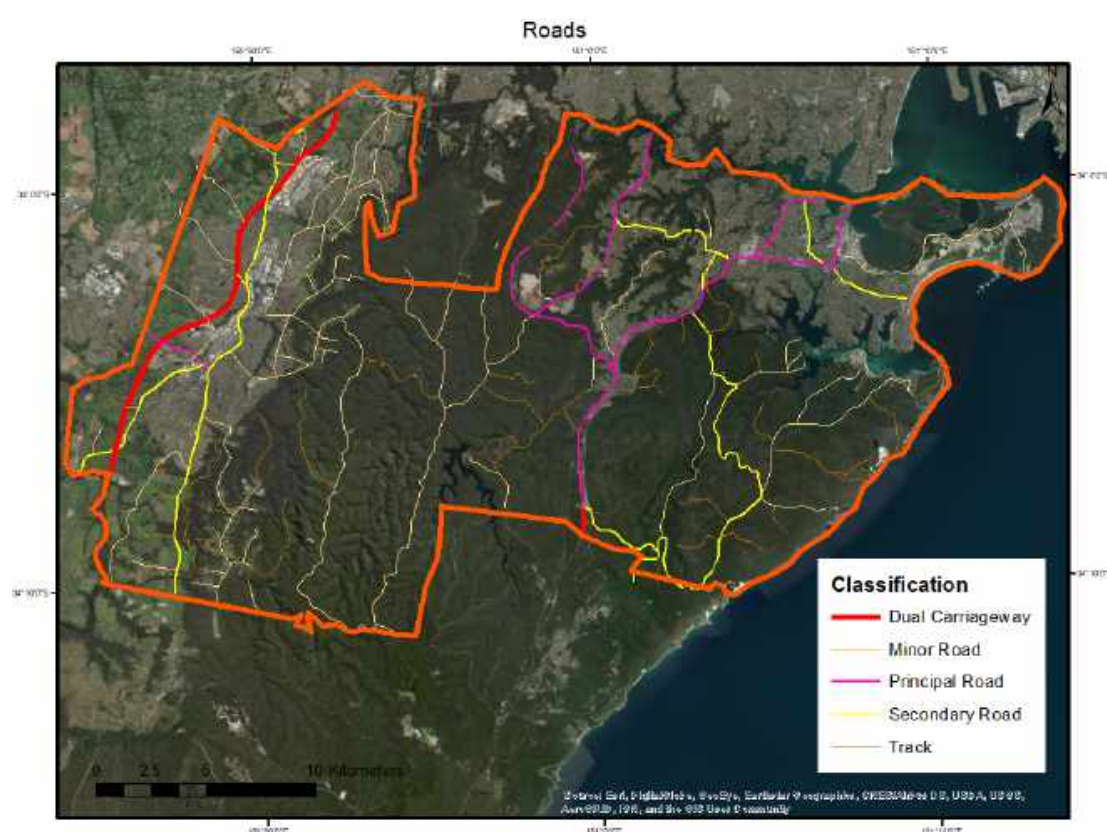
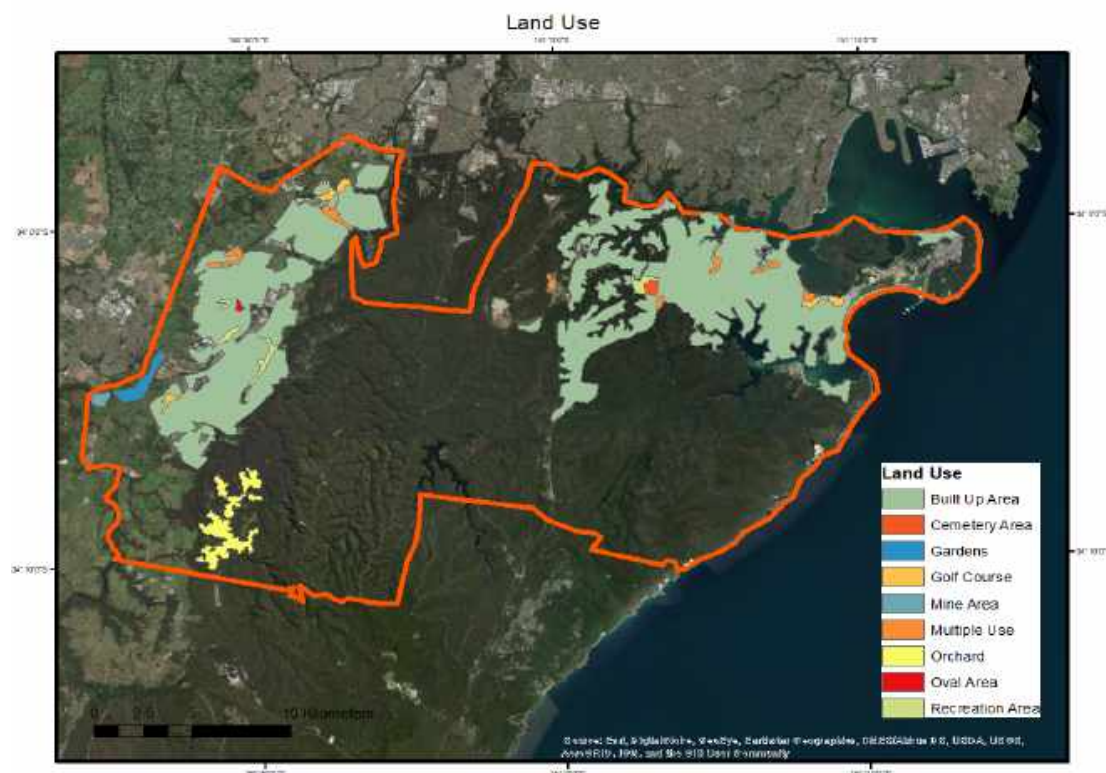| Feature type	Original value	Weight	Reason	Weighted value
Null	1	-	-	1
Track	2	-	No weight given to tracks as effect deemed to be minimal due to their presence predominantly being in national parks	6
Minor	3	3	-	9
Secondary	4	3	-	12
Principal	4	3	-	12
Dual carriageway	20	-	Most significant road type, thus given a maximum value of 20	20

Appendix 2: Map of waterways in the area and table of reclassifications
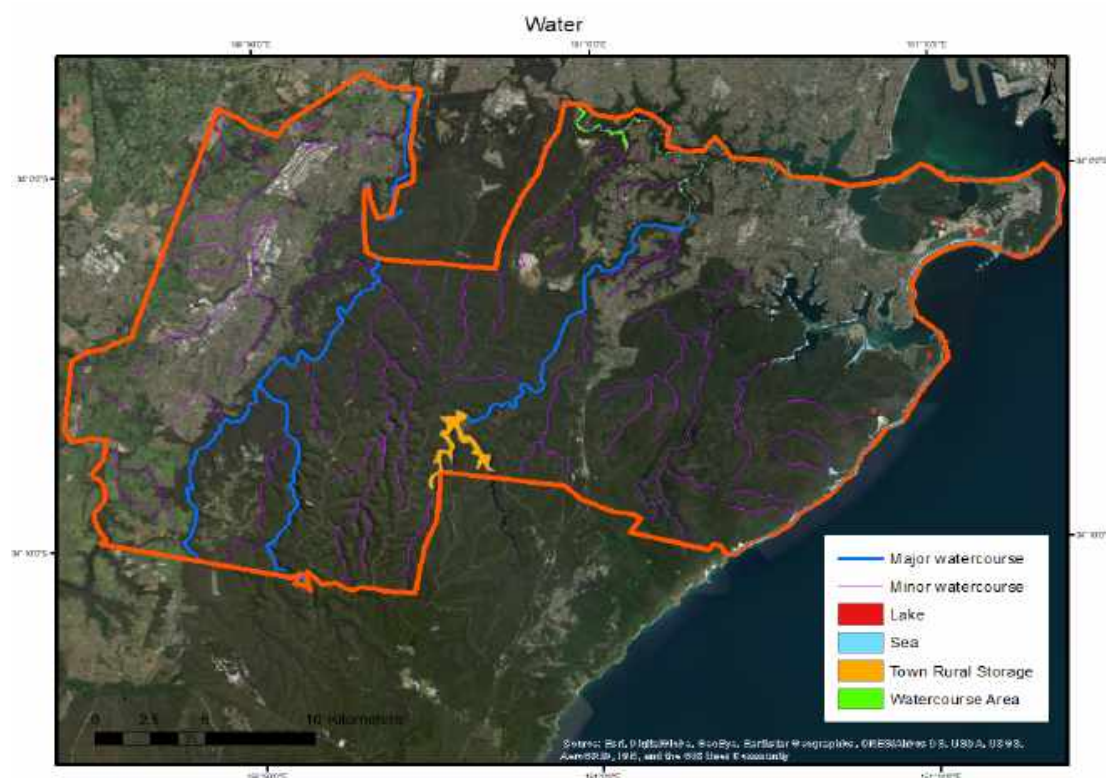
Waterways

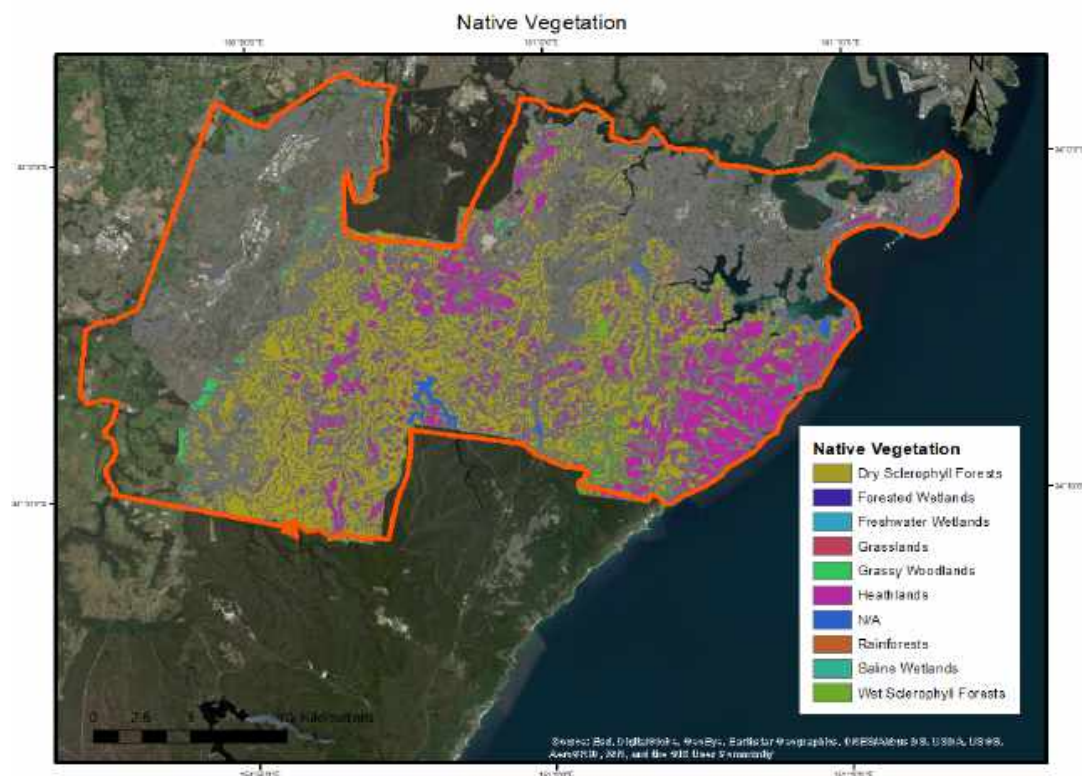| Feature type	Original value	Weight	Reason	Weighted value
Null	1	-	-	1
Minor stream	2	-	-	2
Major stream	3	3	Much more significant influence of major streams	9
Lakes	20	-	-	20
Dam	20	-	-	20
Ocean	20	-	Lakes, Woronora Dam and the ocean all highly unsuitable	20

Appendix 3: Map of land use in the study area and table of reclassifications

Land use

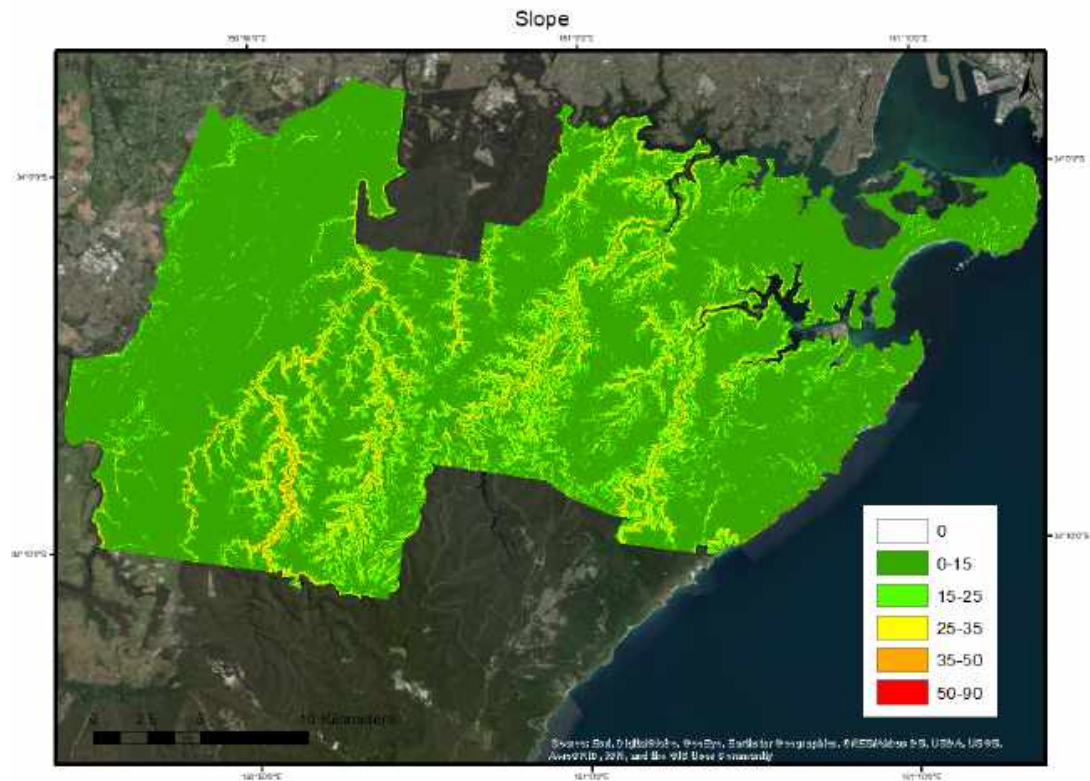| Feature type	Original value	Weight	Reason	Weighted value
Null	1	-	-	1
Orchard	2	-	Lots of koala sightings recorded on the orchard, not deemed to be a significant barrier	2
Mine	20	-	Would present a major barrier	20
Cemetery	3	3	Offers some difficulty to traverse	9
Built-up area	20	-	Would present a major barrier	20
Multiple use	3	3	Unknown	9
Gardens	3	3	Not ideal habitat	9
Ovals	3	3	Offers some difficulty to traverse	9
Golf course	3	3	Offers some difficulty to traverse	9
N/A	3	3	Part of the native vegetation dataset. Unknown areas and, as such, were given an original value of 3 and a weighted value of 3.	9

Appendix 4: Native vegetation in study area

Native Vegetation

Native vegetation

Feature type	Original value	Weight	Reason	Weighted value
Null	1	-	-	1
Heathland	2	-	-	2
Dry sclerophyll	2	-	-	2
Freshwater wetland	2	-	-	2
Grassy woodland	2	-	-	2
Grassland	2	-	The above five native vegetation types were suitable for the selected species in this study.	2
Forested wetland	3	3	-	9
Rainforest	3	3	-	9
Wet sclerophyll	3	3	-	9
Saline wetland	3	3	The above four native vegetation types for less suitable for the selected species within this study.	9

Appendix 5: Reclassified slope layer

Slope

Feature type	Original value	Weight	Reason	Weighted value
Null	1	-	-	1
0-15	2	-	-	2
15-25	3	-	-	3
25-35	4	-	-	4
35-50	5	-	-	5
50-90	8	-	No specific weight given, but assumed that angles over 50^0 would offer slightly more difficulty to traverse.	8