Roads as drivers of change for macropodids

Daniel Ramp

School of Biological, Earth & Environmental Sciences, University of New South Wales, Sydney, NSW 2052, Australia. Fax No. +61 2 9385 1558; E-mail d.ramp@unsw.edu.au.

Abstract

As an iconic and predominantly endemic Australian family of mammals, the Macropodidae are synonymous with Australia's faunal identity. Of the 53 known species prior to European settlement, six have since gone extinct, while many more have suffered significant reductions in range and number. Although individual threats each take their toll (for example human modification of the landscape, hunting, and the influx of invasive predators), it is the combined impact of multiple drivers of change that is of concern. This cumulative impact has the potential to expose even species typically considered common to extinction risk. Recent worldwide attention has been focused on the threat of roads on fauna, a threatening process now being seen as a potential tipping point for species struggling to survive. Here I discuss what is known of the role that roads play in threatening species in the Macropodidae. I examine the direct and indirect effects of roads by collating published information of fatalities (road-kill), landscape modification, and population persistence, contrasting impacts in urban and rural environments. I provide evidence that the impact of roads is more pervasive and potentially catastrophic for some species than previously thought. I discuss attempts to mitigate the impacts of roads on fauna and explore the long-term conservation implications for the Macropodidae.

Introduction

The road environment, which includes the road, the road verge, and surrounding habitat, is increasingly recognised as a major form of environmental disturbance, or 'driver of change' (*sensu* Millennium Ecosystem Assessment 2005). In the last 50 years, road networks around the world have been upgraded and expanded. Recognition of the potential for roads to severely impact on species initially stemmed from collisions with large fauna, primarily ungulates, in Europe and in North America. The effect of the road environment on biodiversity has now spawned a new research field, termed 'road ecology' (Forman 1998; Forman and Alexander 1998). The two most important contributions this field has made are (i) the documentation of just how universal and sizeable the impacts on the environment are and (ii) the documentation of how far impacts extend beyond the bitumen (Forman 2000; Ramp and Ben-Ami 2006). As research in this new field progresses, the considerable role roads play in causing animal fatalities, fragmenting and isolating populations, and ultimately increasing extinction risk is becoming increasingly, and disturbingly, clearer.

Recognition of the impacts of the road environment on Australia's biodiversity encompasses most taxa, yet it is collisions involving larger fauna that occupies the attentions of most conservation biologists and road safety researchers. Although much more research is needed, it is becoming apparent that the effect of the road environment on medium and large sized fauna in Australia, primarily populated by species in the family Macropodidae (with some notable exceptions – e.g. the common wombat, Roger and Ramp 2009), has the potential to cause species decline. Here I collate what is known of how macropodids, members of the Macropodidae, are affected by fatalities, landscape modification, and other indirect effects on population persistence. I highlight the state of knowledge and identify areas of research that require further investigation so that the threat to species and populations can be understood and managed at both local and regional scales.

Drivers of change

The effect of roads must be considered within the context of the range of pressures facing biodiversity today. Unprecedented and multifaceted levels of anthropogenic drivers of change are a global challenge in efforts to conserve of biodiversity (Pimm and Raven 2000). Landscapes of all types are changing to support an expanding human population (Imhoff *et al.* 2004; Foley *et al.* 2005), while extinction rates highlight the pressing need to address threats to the effectiveness of conservation measures (Sekercioglu *et al.* 2004). The challenge for conservation biology is to identify drivers of biodiversity (Possingham and Wilson 2005; Wilson *et al.* 2005) and establish mechanisms to mitigate those drivers.

In Australia, the landscape has changed markedly since European settlement. Past changes in biodiversity have been driven primarily by extrinsic processes like long-term climate change and continental movement, but current driving processes of biodiversity loss are unquestionably linked to human activities. The most important anthropogenic drivers are loss of vegetation cover, invasive species, overexploitation, disease, pollution, and rapid climate change (Mace *et al.* 2005). Drivers directly and indirectly affect ecosystems at many spatial and temporal scales, and with complex interactions. Understanding how these drivers and their interactions affect local populations, biodiversity and ecological functioning is essential to conservation and management efforts.

Urbanisation

One of the primary reasons for the increasing threat of roads is global urbanisation (Daily 1997). As urban areas expand road density and traffic volume increase. Three billion people live in cities world-wide and this number is expected to double over the next 50 years (Crane and Kinzig 2005), while the number of urban areas with over one million people is expected to grow by over 40% between 2000 and 2015 (Crane and Kinzig 2005). In the USA, urbanisation has been identified as a primary cause, singly or in association with other factors such as roads, for declines in more than half the species listed as threatened or endangered under the U.S. Endangered Species Act (Czech *et al.* 2000; Miller and Hobbs 2002).

Aside from dramatically altering vegetation cover, urbanisation has long been recognised as changing landscapes and isolating pockets of suitable habitat or refugia for many species (Fahrig 2003; Adams 2005). Urbanised regions now have severely reduced wildlife populations, with many remaining species considered endangered (Flannery 2004). Environmental refugia in the urban landscape often provide the last pockets of refuge for species that were once widespread and are important for both local and regional biodiversity (Margules and Pressey 2000; Cornelis and Hermy 2004).

Australia is no exception and many protected areas close to urbanised areas are impacted upon by increasing road densities and traffic. One example is the Royal National Park, situated just south of Sydney, New South Wales (NSW) (Australia's largest city, population 4.28 million in 2006). The oldest national park in the world (declared as 'The National Park' in 1879), it is surrounded by major highways and urban development and is criss-crossed by a network of roads. Calculations show that 58 % of the park is within 1 km of sealed roads with speed limits of either 60 or 80 kmh^{-1}. If unsealed roads and fire trails are included 86 % of the park is within 500 m of a road (Figure 1). This important conservation reserve is a maze of roads; fragmenting wildlife and removing them via collisions with vehicles. As I will show, macropodids that occur in these peri-urban reserves frequently struggle to maintain viable populations.

Transportation networks and rural landscapes

The role of transportation as a driver of change is now widely accepted (Forman *et al.* 2003). There were 15.3 million registered vehicles in Australia in 2008 (Australian Bureau of Statistics), predominantly using urban roads but also moving among cities. Transportation corridors to facilitate the movement of goods among metropolises and provide commuter traffic with unprecedented freedom are a significant contributor to the impact of roads on wildlife. Road infrastructure is continually being upgraded to allow for greater traffic volumes and speed, particularly on rural highways. The carcases of large fauna are commonly observed rural highways; predominantly kangaroos in Australia (Klöcker *et al.* 2006). Transportation of freight by large trucks and road trains is a considerable contributor to this problem (although few data exist). Freight vehicles travel in excess of 157,000 million tonne-kilometres per year in Australia (Australian Bureau of Statistics), regularly driving rural roads often without the luxury of slowing down or swerving: the timely delivery of goods is their priority. Many rural highways are known for the frequency of kangaroos and wallabies on the roadside at night.

In rural environments it is the combination of vehicle frequency and speed that is generally regarded as the primary cause of fauna fatalities on roads (Forman and Alexander 1998; Hubbard *et al.* 2000; Jones 2000; Trombulak and Frissell 2000;

Dique *et al.* 2003; Seiler 2003). Research typically assumes that there is a linear correlation between volume, speed and collision frequency, yet disturbance generated by busy roads can sometimes lead to a lower rate of fatalities than on less-travelled roads with similar speed limits (Clevenger *et al.* 2003). This pattern has been observed with kangaroos, where a rural highway with low traffic volume (60 vehicles per day) had a fatality rate (0.035 per km per day pre-drought), similar to roads with much higher traffic volumes (Lee *et al.* 2004). It follows that high fatality rates may be more likely to occur on roads with high speed limits and moderate to low traffic volumes adjacent to habitat containing abundant wildlife. It has long been recognised that road environments in Australia are unique, as often the only remaining habitat for wildlife exists along road corridors (Bennett 1991). While this undoubtedly provides habitat for many species, it is the combination of habitat with fast moving vehicles that is of concern for macropodids and other fauna.

Roads as threatening processes

Most of the impacts of roads on the environment have been documented in literature unrelated to macropodids. Roads have been shown to affect microclimate (Ellenberg *et al.* 1981 - cited in Forman et al. 2003), wind flow (Ahrens 1991), run-off and water flow (Federal Highway Administration 1996), create noise pollution (Reijnen *et al.* 1997) and facilitate the dispersal of both plants and animals (Tikka *et al.* 2001), including weeds (Ullmann 1998), feral animals (Seabrook and Dettmann 1996; Stiles and Jones 1998) and native species (Spooner *et al.* 2004). Roads result in a direct loss of habitat, including the road surface and the road verge. Conversely, the road verge can also provide resources and habitat for many species (Bellamy *et al.* 2000). However, negative impacts can be detected far from the road edge (Reijnen *et* *al.* 1995; Goosem 2000; Ortega and Capen 2002; Laurance 2004), leading to avoidance of these environments by many species (Forman *et al.* 2002) and changes in the behaviour of roadside populations (Foppen and Reijnen 1994). Roads often bisect habitat and, depending on the type of road, prevent or restrict movement. This is often termed the 'barrier effect' and it has the potential to isolate populations and cause decline by preventing access to resources and mates (Richardson *et al.* 1997; Gerlach and Musolf 2000). Vehicles travelling on roads have perhaps the most significant impact on fauna when they collide with them (Ramp *et al.* 2005a). If fatalities are biased towards particular sex-age classes (Coulson 1997a) there is the potential for the structure of local populations to be altered. Even when unbiased, fatalities have the potential to cause population decline (Mumme *et al.* 2000; Lopez 2004; Ramp and Ben-Ami 2006). Lastly, roads create welfare issues for the animals and humans injured and killed (Williams and Wells 2005; Ramp and Roger 2008; Rowden *et al.* 2008).

Evidence of impact on macropodids

The macropodids are a diverse group that occur throughout Australia. Aside from the banded hare-wallaby (*Lagostrophus fasciatus*), the only surviving member of the subfamily Sthenurinae, there are five sub-groups of the subfamily Macropodinae, the only other subfamily in the family Macropodidae (Strahan 2002). These sub-groups are (a) the kangaroos, wallabies and wallaroos from genera *Macropus* and *Wallabia*, (b) the rock-wallabies, pademelons and quokka from genera *Petrogale*, *Thylogale* and *Setonix*, (c) the nailtail wallabies and most hare-wallabies from genera *Onychogalea* and *Lagorchestes*, (d) the tree-kangaroos from the genus *Dedrolagus*, and (e) the New Guinean forest wallabies from genera *Dorcopsis* and *Dorcopsulus*.

Evidence for roads as drivers of change can be distinguished as either direct or indirect in nature. Indirect evidence can come in three forms. Large-scale information on crashes with vehicles is often gathered by government and insurance agencies. In the scientific literature, both small- and large-scale evidence is reported through the brief mention of road impacts on a species or population of interest. Lastly, community groups and concerned individuals often collect information at small scales that can prove invaluable for assisting with the implementation of localised mitigation measures. Direct evidence comes through the targeted scientific study of the direct and indirect impacts of roads at both small and large scales.

General evidence

General information on the effects of roads on the macropodids varies among the different groups. For the six species of kangaroos in sub-group (a), the toll on individual animals, on local populations and across species' ranges can still only be speculated upon for each species. As their ranges are mostly extensive [except for the black wallaroo (*Macropus bernardus*)], accurate population estimates are difficult to obtain. Considerable effort in conducting aerial surveys to estimate distributions and abundance is undertaken (Pople *et al.* 2000) but uncertainty in actual population numbers still exists. Likewise, comprehensive assessments of use of the road environment by kangaroos are yet to be conducted (although some unpublished data exists). Piecing together how roads affect these species is a necessary but complicated task, particularly because the kangaroos must also contend with drought, habitat loss, shooting (including legal and illegal culling and harvesting), and impending transformations associated with climate change. There is a pressing need to assess how these threatening processes, including roads, combine to impact on kangaroo populations at both local and regional scales.

The kangaroos include the largest species to be encountered on roads in Australia. Adult male red kangaroos (*Macropus rufus*) can reach weights of 85 kg while eastern grey kangaroos (*Macropus giganteus*) range to 66 kg (Strahan 2002). Both can stand to around two metres in height. While not the same as colliding with moose or elk (Seiler 2005), colliding with a large kangaroo is a dangerous experience for vehicle occupants despite human fatalities not being common (Abu-Zidan *et al.* 2002). Insurance companies frequently report that the average cost of repairing damage from a collision with a kangaroo ranges between two and seven thousand Australian dollars, while a vehicle-accessory industry has spawned vehicle adornments in an effort to reduce vehicle damage (roo-bars) and the likelihood of a collision (Shu-Roo), neither of which have much success (see Grzebieta and Rechnitzer 2001; Bender 2003).

Indicative evidence of the impacts of roads on kangaroos can be derived from reported crashes between animals and vehicles, such as those included in the NSW Roads and Traffic Authority's Traffic Accident Database System of NSW (TADS). TADS only contains crash information when road crashes are reported to NSW Police, and hence infrequently in the case of animal involvement. Crashes are only reported to police when either human injuries occur or vehicle damage requires the vehicle to be towed. Yet these data are extremely useful because they cover a large area, are comparable among years, and are often the only source of information. Ramp and Roger (2008) queried the TADS database between 1996 and 2005 and determined that animals were responsible for 22 human fatalities and 1,462 human injuries out of 5,119 reported crashes with animals. Sixty percent of human fatalities were caused by kangaroos or wallabies (no distinction made). Spatial analysis of these crashes enabled state-wide hotspots for collisions with kangaroos or wallabies to be identified: information that could be used to prioritise state-based mitigation strategies. The many limitations of these data and suggestions for improvement are discussed in detail by Ramp and Roger (2008).

Of the eleven wallabies in sub-group (a), most members of the group have been documented to be impacted upon by roads. Given the extent of its range, the swamp wallaby (*Wallabia bicolor*) is perhaps one of the more frequently observed, although the red-necked wallaby (*Macropus rufogriseus*) is also prominent (Ramp *et al.* 2005a). Given the overlap in range and land utilised for human habitation, it is not surprising that fatalities on roads are a problem for many swamp wallabies populations (e.g. Ramp *et al.* 2005a). Populations are often isolated in peri-urban remnant habitat that are surrounded by major highways or criss-crossed by sealed roads (Ben-Ami *et al.* 2006; Ramp *et al.* 2006). Fatalities have been shown to be directly responsible for the decline of swamp wallaby populations, over and above impacts from predation (Ramp and Ben-Ami 2006). Ramp and Ben-Ami (2006) found that a predicted 90 % decline in the population over the next 100 years could be reduced to only 10 % if annual female swamp wallaby fatalities were reduced by 20 %. To achieve a similar reversal of the predicted decline, the influence of fox predation on swamp wallabies would need to be reduced by 70 %, an almost impossible target.

Most of the macropodids in sub-group (b) have been listed on the threatened species list for some time, with the exception of the pademelons (although they are listed as vulnerable in some areas). Habitat loss, fragmentation and predation by introduced fauna like the red fox (*Vulpes vulpes*) are the primary reason for their precarious existence; however, fatalities on roads have also been documented as having a significant impact on remaining populations. Among the many threats to quokka (*Setonix brachyurus*) populations, Hayward *et al.* (2005) identified that 40% of deaths in a Western Australian study were attributable to collisions with vehicles.

The highly endangered bridled nailtail wallabies (*Onychogalea fraenata*) in sub-group (c) are only found in Taunton National Park in central Queensland, which only has unsealed tracks and is not open to the public. No cases of fatalities on roads have been documented within the park or at reintroduction sites, which also have only unsealed roads (D. Fisher, pers. comm.). In contrast, northern nailtail wallabies (*Onychogalea unguifera*) are reasonably common, occurring across much of northern Australia. Although their geographical distribution and abundance does not appear to have altered much since European settlement, the removal of habitat for agriculture is a major threat to their populations (Ingleby 1991). Despite their remoteness, they benefit from roads by being provided with access to their favoured ground-layer herbs (S. Ingleby, pers. comm.). These plant species would typically have become available after fires or at 'run-on' areas; circumstances mimicked by the road verge. As a consequence, northern nailtail wallabies are frequently observed as carcases on roads such as the Stuart Highway. No population studies have been conducted to assess how these might contribute to local extinction risk.

Concern over the impact of roads has been noted for the tree-kangaroos of sub-group (d) in Australia's wet tropics. Newell (1999) confirmed that collisions with vehicles were a significant source of mortality, in addition to habitat loss and fragmentation. No published evidence of road impacts exists for the New Guinean forest wallabies of sub-group (e).

Direct evidence

In Australia, scientific studies on the effect of roads on Macropodids target three primary areas of research, although they are not mutually exclusive or all encompassing. Most research has focussed on documenting collision rates for different lengths of road and for different species. More recently, research has begun to examine the fragmenting effects of roads as well as what impacts roads have on species populations.

Collisions with vehicles

Australia’s macropodids present a novel group of species to study. Ungulates (deer, moose and elk) are responsible for most animal-vehicle collision research in the US, Canada and Europe. They are often killed on roads as they have large home ranges and often migrate (Groot Bruinderink and Hazebroek 1996; Seiler 2004). In contrast, none of the macropodids are migratory; being sedentary with fixed home ranges as adults (Jarman and Taylor 1983; Priddel 1988; Norbury *et al.* 1994; Dawson 1995). Exceptions exist, however, as sub-adult males often disperse to establish new territories (Jarman 1991; Horsup 1994) and a small proportion of red kangaroos are known to disperse over many kilometres (Priddel *et al.* 1988). Most macropodids that encounter the road therefore do so for three primary reasons: a) they are moving through the landscape within their normal home range, either to find a mate, food or water, or to assess the state of neighbouring habitat, b) they are attracted to the road verge in order to gain access to resources on the verge or water from run-off and condensation from dewfall, or c) they are dispersing. Positive selection for road-side habitat has been shown for kangaroos along a rural highway in far-west NSW (Klöcker *et al.* 2006).

Being located on or next to the road makes an individual susceptible to colliding with a vehicle. The collection and reporting of statistics on the number of macropodids killed on roads is currently conducted by scientific researchers and concerned members of the community. While state road authorities and local councils regularly remove carcases from roadsides, little or no data is retained. A number of small-scale road-kill studies employing systematic surveys have been reported in the literature, beginning with Coulson (1982) and followed by Osawa (1989). It was not until the late 1990s that interest in the issue gathered pace in an effort to broaden the information base on macropodid fatalities (Coulson 1997a; Cooper 1998; Lee *et al.* 2004; Taylor and Goldingay 2004; Ramp *et al.* 2005a; Klöcker *et al.* 2006; Ramp *et al.* 2006). Unpublished data also exist in reports and thesis (Brown 2001; Magnus *et al.* 2004). Disappointingly, most cover less than 100 km of road and are not conducted over an appropriate length of time. There is a lack of comparability among studies as they are conducted within different environments, on different types of roads with different traffic volumes, and for different wildlife populations that have inherently different sizes. A number of papers have highlighted the disparity between surveys conducted under different climatic conditions (Coulson 1989; Lee *et al.* 2004). The frequency of surveys also confounds comparisons as some studies are conducted daily while others are periodic. The calculation of daily rates from periodic surveys is problematical if the time between sampling allows for fatalities to be missed (e.g. Coulson 1982; Hobday and Minstrell 2008).

These difficulties make the reporting of state-wide or even nation-wide statistics challenging: something government agencies, local councils and the public need to be overcome. For the macropodids, published findings of daily fatality rates range between 0.0006 and 0.042 per km per day (Table 1). The highest published rate comes from Kosciusko National Park where in 2003 eastern grey kangaroos, swamp wallabies and red-necked wallabies were reported to be killed at a rate of 0.044 per km per day (Ramp *et al.* 2005a). It is tempting to extrapolate these rates. For example, NSW has 182,006 km of road, divided almost equally between bitumen and gravel roads. Fatality rates of 0.01 or 0.04 would result in either 1,820 or 7,280 macropodids killed on NSW roads every day respectively (or between 664,321 and 2,657,287 per year). These calculations do not, however, account for different rates between bitumen and gravel roads, for variation in traffic volume, and for differences between urban and rural roads. They also assume that the ranges of species being killed are constant across the state and do not allow for changing climatic conditions. Given the large degree of spatial and temporal error that is associated with estimating state-wide or even nation-wide totals from these small amounts of data, it is clear we must obtain more high quality spatial and temporal data of fatality rates under all conditions before we can be confident of our predictions.

Barrier effects

The barrier effect of roads refers to the segregation that can occur from the restriction of movement across the road. Hypothesised implications are the loss of genetic diversity and a few examples of this occurring exist (Gerlach and Musolf 2000). The road environment can also alter the behaviour of species, changing their intra- and inter-specific interactions (Reijnen *et al.* 1997). There is great variation in the Macropodidae: not only in body size and morphology, but also in behaviour and sociality (Coulson 2009). These differences have implications for how the road environment impacts on macropodids. In rural Australia we know that roads influence the movement and space use of kangaroos (Lee 2006). In these environments dispersal and movement by individuals should protect kangaroo populations from genetic drift resulting from any fragmentation effects that might occur; as suggested in the context of reserves by Tenhumberg *et al.* (2004).

For wallabies, the road environment may indeed pose significant restrictions on movement and space use. Most research on the barrier effect has focussed on small mammals, where road crossings are prevented when the road reaches a certain width (Goosem 2001). That wallabies are frequently killed on roads suggests that while crossing may be difficult, and often unsuccessful, crossing nevertheless does occur. There is little published research examining how wallaby species use roadside habitat (but see Ramp *et al.* 2006), although there is some evidence that wallabies living in proximity of major highways alter their use of space and behaviour in order to adapt to these environments (Ramp and Ben-Ami, unpublished data).

Population effects

Surveys of the populations of the main four kangaroo species are typically conducted using aerial survey techniques, as they are large and often forage in open country (Caughley and Grigg 1981; Priddel 1988; Pople *et al.* 2000). Estimates suggest that the total numbers of kangaroos in Australia are in the millions but numbers are highly susceptible to annual variation, primarily dictated by climatic conditions. The kangaroos do not exhibit an even distribution across the landscape: rather they exhibit a patchy distribution in line with suitable habitat and resources at different scales (Ramp and Coulson 2002; Coulson 2009). At regional scales, their distributions are comprised of many local populations that are variously connected by dispersing individuals. It was first suggested by Coulson (1997a) that road-based fatalities might be influencing the demographic structure of populations. In reporting male bias in fatalities he speculated whether males of some species come into contact with roads more often than females, thereby altering population sex-ratios. There does not appear to be any behavioural reason that would make males more likely to collide with a vehicle than females, hence bias must presumably occur through a higher propensity to be on the road. Spatial segregation, common in the macropodids (MacFarlane and Coulson 2005; Coulson *et al.* 2006), is also likely to affect the propensity for different sex or age classes to be killed on roads (Morrissey 2003; Lee *et al.* 2004).

Changes to population structure, isolation of sub-populations, and loss of animals from collisions with vehicles have the potential to contribute to population decline (Ben-Ami and Ramp 2006). This is an under-explored area of research, not just for the macropodids but for most species (Forman *et al.* 2003). Hayward *et al.* (2005) reported that although fatalities of the threatened quokka in the northern jarrah forest of Western Australia are infrequent (two of eight recorded deaths over a 25 month period), the impact on the population was considerable. Recent evidence suggests that even for species considered common and relatively resilient to human disturbance, such as the swamp wallaby, roads can be a major contributor to population decline (Ben-Ami *et al.* 2006; Ramp and Ben-Ami 2006). While on their own roads may not directly cause the extinction of macropodid species, there is good evidence to suggest that they may be causing localised extinctions of macropodid populations living adjacent to roads. Considered alongside other drivers of change, roads have the potential to significantly contribute to population decline.

Mitigation

Much effort has been spent examining the effectiveness of various mitigation strategies for reducing fatalities of animals on roads or improving the permeability of roads (Waring *et al.* 1991; Groot Bruinderink and Hazebroek 1996; Romin and Bissonette 1996). Given that the impact of the road environment on wildlife is considerable, research that identifies how to prevent collisions and minimise environmental impact is a high priority for conservation managers. Most research has been conducted internationally (Clevenger *et al.* 2001a; Clevenger *et al.* 2001b; Dodd *et al.* 2004; Jaeger and Fahrig 2004), however Australian researchers have begun to make some progress. This is important as the adoption of strategies implemented overseas has often proved unrewarding in Australia (Lintermans 1997).

One such mitigation strategy that has been used in Australia over the last 20 years is the Wildlife Warning Reflector (Strieter Corporation 2001). The devices are designed to reflect oncoming vehicle headlights into the eyes of wildlife on the roadside to frighten them before the vehicle arrives. Despite their popularity, scientific evidence for their effectiveness in reducing collisions with deer suggests they have little or no effect (Waring *et al.* 1991; Ujvari *et al.* 1998). Recent evidence in Australia suggests that they may have limited efficacy with macropodids (Ramp and Croft 2006). Not only have captive trials failed to detect a response in macropodids that could lead to a reduction in collisions, but it is also likely that the effectiveness of any mitigation strategy is going to vary considerably among species (Ramp *et al.* 2005b; Lee *et al.* this volume).

As a mitigation strategy, the scaring of macropodids away from oncoming vehicles using sound as a deterrent has some merit. The use of sound as a warning cue is widespread in the animal kingdom and sounds are used by kangaroos and other macropodids in this fashion (Jarman 1991; Coulson 1997b; Bender 2005). There is a strong behavioural basis to encourage the development of an auditory repellent device in relation to roads. Devices currently available that claim to do this using ultrasonic frequencies have been criticised in the scientific literature (Bender 2003; Muirhead *et al.* 2006). A more fertile area of research would be to explore the response of kangaroos to natural sounds derived from themselves (like foot thumps) or predators (Bender 2005; Bender 2006; Rose *et al.* 2006); as long as the delivery mechanism could function amidst the normal sounds vehicles produce.

Physical structures can be implemented along roads to assist with, or prevent, animal movement across roads. There is a lack of data on the effectiveness and suitability of wildlife crossings for different species in different environments. While these measures would not be cost-effective along the vast lengths of rural roads, hotspots of high fatality rates on highways and major roads in peri-urban areas may provide suitable locations for physical structures. Some research in Australia has examined common strategies such as the installation of fences to prevent movement of wildlife and the installation of underpasses to facilitate the safe passage of wildlife (Mansergh and Scotts 1989; Australian Museum Business Services 1997; Jones 2000; Abson and Lawrence 2003; Taylor and Goldingay 2003). These studies report various levels of success, but often the definition of success is problematical (i.e. the recording of prints within underpasses without quantifying reductions in fatalities). To date, no study has linked the installation of a physical road structure with a reduction of macropodid fatalities or the facilitation of movement where previously none was possible, although evidence has been obtained for other species both in Australia and elsewhere.

Conservation implications

Variation in response to the road environment may occur at both the species and individual level (Reijnen *et al.* 1996; Forman *et al.* 2003; Ramp *et al.* 2006; Lee *et al.*

this volume). This variation in suitability and susceptibility among species to roads has implications for species survival and the functioning of ecosystems (Loreau 2000). Certain morphological, biological and ecological traits may confer either suitability or susceptibility (most likely along a continuum) to road-impacted environments (Forman and Alexander 1998). Presumably, highly susceptible species are lost soon after a road is built, while the suite of species with more subtle susceptibilities gradually reduce in richness and abundance (Findlay and Bourdages 2000). However, roads can also attract species because they facilitate movement (Getz *et al.* 1978; Bennett 1991) and provide food and water on the verge for species that can adapt to road environments. Identifying how different macropodids respond to roads will be crucial for defining the course of conservation efforts.

Although it is rare to find a population that is threatened solely because of roads, the combination of road impacts with other drivers of change may lead to decline and local extinction. It seems that where macropodid populations are isolated and relatively restricted in size, mortality associated with collisions with vehicles can jeopardise the long-term viability of local populations (Ramp and Ben-Ami 2006), and occasionally the entire species (Hayward *et al.* 2005). There is also no doubt that the loss of individuals of common species, like the kangaroos and wallabies in sub-group (a), is occurring at significant rates (Ramp *et al.* 2005a).

Until there are reliable statistics on how many macropodids are being killed it is difficult to assess just what implications this loss has for the long-term viability of this iconic group of species. It is imperative that systematic surveys of directly comparable fatality rates are collected under a range of conditions (environments, traffic volumes, speeds, road types, climate) so that reliable modelling of the numbers killed can be used to assess the overall impact on populations. With increasing pressure from landscape change, predation from feral animals, legal and illegal shooting, and climate change, pressure from roads may be the final nail in the coffin for many macropodid populations. The opportunity exists for governments to legislate for changes to the way in which roads are designed, forcing road construction companies to integrate environmental mitigation options such as fences and underpasses into the development phase of road building: a far more cost-effective and politically sensitive approach than retrofitting.

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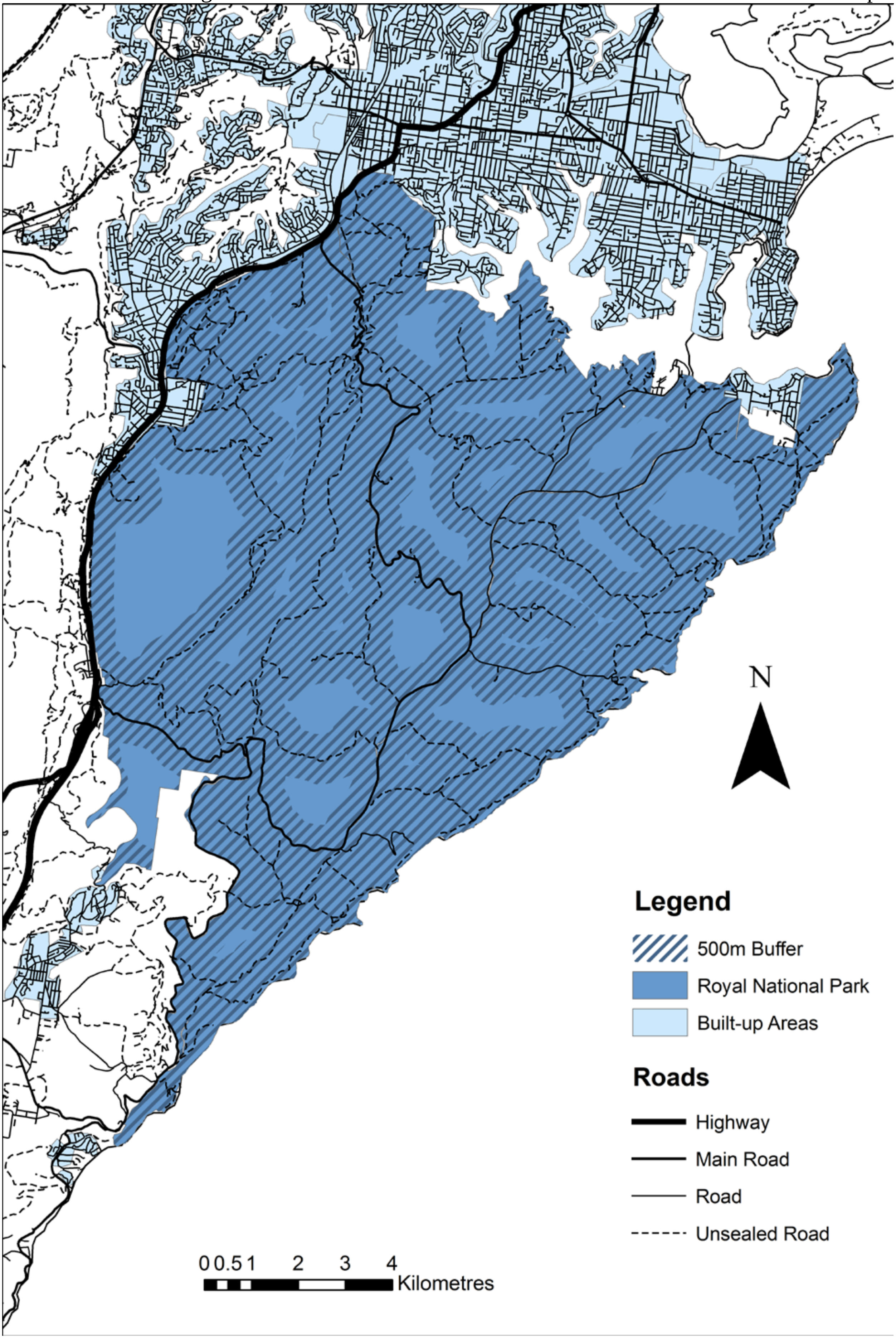
Table 1. Scientific publications reporting on fatality rates for macropodids in Australia. Species names are EGK (eastern grey kangaroo), WGK (western grey kangaroo), RK (red kangaroo), E (Euro), SW (swamp wallaby), RNW (red-necked wallaby), TP (Tasmanian pademelon) and BW (Bennett's wallaby).

Source	**Time Period**	**Sampling period**	**Frequency**	**Location**	**Climate**	**Environment**	**Road type**	**Traffic volume (cars day^{-1})**	**Speed (kmh^{-1})**	**Road surface**	**Species**	**Road-kill**	**Road length (km)**	**Average (km^{-1} day^{-1})**
(Vestjens 1973)	1970 - 1972	24 trips	Monthly	South-eastern NSW	Temperate	Rural	Highway	Various	100	Mostly sealed	EGK, RK	4	301	0.0006
(Coulson 1982)	1975 - 1980	124 trips	Periodic	Heathcote, VIC	Temperate	Rural	Highway	~ 1,000	100	Sealed	EGK, SW	32	20	0.013
(Osawa 1989)	1981 - 1982	365 days	Monthly	North Stradbroke Island, QLD	Tropical	Peri-urban	Road	Unknown	100	Sealed	SW	127	23	0.015
(Taylor and Goldingay 2004)	2000 - 2001	140 days	Weekly	Byron Bay, NSW	Temperate	Rural	Highway, road	5,000 – 20,000	60 - 100	Sealed	SW	13	100.3	0.0009
(Ramp *et al.* 2005a)	1998 - 2003	6 years	~ Twice Daily	Kosciusko National Park, NSW	Temperate	Rural	Highway	~ 500	100	Sealed	EGK, SW, RNW	2750	40	0.031
(Klöcker 2003)	2002	168 days	Every two days	Fowlers Gap, NSW	Semi-arid	Rural	Highway	~ 50	100	Sealed	EGK, WGK, RK, E	125	21.2	0.035
(Ramp *et al.* 2006)	2003	143 days	Daily	Royal National Park, NSW	Temperate	Peri-urban	Road	~ 3,000	60 - 80	Sealed	SW	14	22	0.0045
(Hobday and Minstrell 2008)	2001 - 2004	154 trips	Periodic	Tasmania	Temperate	Peri-urban, rural	Highway, road	Various	Various	Mostly sealed	TP, BW	647	99.2*	0.042

* Total distance travelled over 154 trips was 15,275 km, for which the average distance travelled per trip is 99.2.

Figure 1. The road effect zone in the Royal National Park, NSW Australia. The buffered 500m area surrounding all roads, including unsealed roads, accounted for 86% of the entire reserve.


N
Legend
500m Buffer
Royal National Park
Built-up Areas
Roads
Highway
Main Road
Road
Unsealed Road
0 0.5 1 2 3 4
Kilometres