The effects of an arid-zone road on vertebrates: what are the priorities for management?

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ABSTRACT

The strategic management of the impacts of roads on vertebrates is hampered by a lack of information on 1) the scale of such impacts in different ecosystems, 2) the responses of populations and communities, and 3) the relative vulnerabilities of various vertebrate groups. We therefore examined the effects of a typical road in an arid ecosystem on kangaroo populations and communities, threatened small mammal species (*Sminthopsis macroura* and *Leggadina forresti*), and small mammal and lizard communities over two years. We determined which vertebrate populations and communities were negatively affected by the road, thereby informing management priorities for mitigating road effects. The study was conducted along the Silver City Highway on the UNSW Arid Zone Research Station, Fowlers Gap, in north-western New South Wales. We found that the road influenced the spatial distribution of kangaroos relative to the road, particularly those of *Macropus rufus*, and was associated with increased kangaroo mortality. Further, the road altered the composition of small mammal and lizard communities and reduced the abundance of *S. macroura*. However, roadkill of kangaroos did not significantly affect the population demographics or community composition of kangaroos. There were no changes in sex ratios (female dominance) which would threaten the sustainability of *S. macroura* and *L. forresti* populations near the road. Further, changes in the species composition of small mammal and lizard communities were likely to be localised near the road, rather than altered at larger scales, because the differences in resource availability driving community differences were restricted to a narrow band immediately adjacent to the road. Thus, none of the vertebrate taxa studied were significantly threatened by the presence of the road and its associated vehicle traffic. Even so, we recommend that management efforts focus on reducing the frequency of kangaroo roadkill (the most serious animal and human welfare issue) through encouraging the growth of shrubs and low vegetation unpalatable to kangaroos adjacent to arid-zone roads. Such a management strategy could also have positive flow-on effects for other vertebrate taxa, and could restore the natural integrity of arid landscapes near roads.

Key words: roads, vertebrates, kangaroos, small mammals, lizards, arid ecosystems, arid-zone, management, roadkill.

Introduction

Since the arrival of modern vehicles and the subsequent expansion of roads to carry them, there has been an "uneasy embrace" between humans and wildlife (Forman *et al.* 2003). Roads range from dirt tracks through to bitumen-sealed multilane highways and they now form extensive networks over the landscape (Forman *et al.* 2003). The density of these networks is generally a function of human population density but road networks nonetheless traverse sparsely populated regions in order to join scattered human population centres (Fig. 1 for the Australian road network). Thus, road networks extend indiscriminately through different ecosystems and bring humans and wildlife from many ecosystems into close proximity. Such proximity may be "too close for comfort" from both the perspective of humans involved in wildlife-vehicle collisions, and that of wildlife traversing and living near roads.

Roads and their associated traffic have many negative effects on wildlife. Most research has focussed on vertebrates, where roads may act as barriers to movement (Barnett *et al.* 1978; Mader 1984), thus fragmenting populations. Such barrier effects are augmented when animals alter their movements to avoid roads (Gerlach and Musolf 2000; Dyer *et al.* 2002; Shine *et al.* 2004; Steen and Gibbs 2004) and also avoid crossing roads (Richardson *et al.* 1997; Goosem 2001; Rondinini and Doncaster 2002). Alternative to avoidance, some animals may be attracted to roads (Lee *et al.* 2004; Aresco 2005; Tanner and Perry 2007), and this attraction may increase wildlife mortality (Hels and Buchwald 2001; Aresco 2005; Ramp *et al.* 2005; Seiler 2005). Moreover, species fitness may be directly (reproductive output and success: Fernandez 1993; Ortega and Capen 1999) and indirectly (physiological states: Wasser *et al.* 1997; Tanner and Perry 2007) impaired by roads.

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With so many negative effects of roads on vertebrates, as well as the harmful impacts of wildlife-vehicle collisions on humans, management actions must be taken to mitigate negative effects, with greater urgency if a species is threatened with extinction. However, strategic management of these impacts is hampered by a lack of information on 1) the scale of the effects from road features to landscape types and ecosystems, 2) the impacts of roads on populations and communities, and 3) the relative vulnerabilities of various vertebrate groups to the effects of roads.

The scale of road effects is likely to vary between ecosystems due to the different ways that roads interact with the ecological processes of different ecosystems (Gutzwiller and Barrow 2003; Brooks and Lair 2005). For example, water run-off from road surfaces is likely to have greater effects on plant growth near roads in arid ecosystems as compared with more mesic environments; water is more limiting to primary productivity in arid compared with mesic ecosystems (Westoby 1980; Stafford Smith and Morton 1990). Effects of enhanced plant growth along road edges in arid ecosystems may subsequently affect faunal distributions and abundance more so than in mesic environments, due largely to the patchier distribution and more limited amounts of food resources in arid regions (Stafford Smith and Morton 1990). Few studies have specifically addressed the variation between ecosystems in the nature and scale of road effects (but see Garland and Bradley (1984), and brief comments by Boarman *et al.* (1997), Goosem (2001) and Forman *et al.* (2003)) and management strategies that address particular road effects in one ecosystem may not be appropriate in other ecosystems.

Importantly, the lack of information on the effects of roads on higher-order ecosystem responses (Spellerberg 2002; Forman *et al.* 2003) impairs the development of strategic management to conserve vertebrates. To date, most studies have concentrated on documenting the effects of roads on individual species and identifying potential causes for such effects. Only a handful of these studies have subsequently investigated species-specific effects on population structure and health, and on whole communities (Jones 2000; Mumme *et al.* 2000; Lee *et al.* 2004; Aresco 2005). Information on the effects of roads at higher-order ecosystem levels is essential for conservation management because it may identify vulnerable populations (especially of threatened species) and communities that can be targeted for management action (Burgman and Lindenmayer 1998).

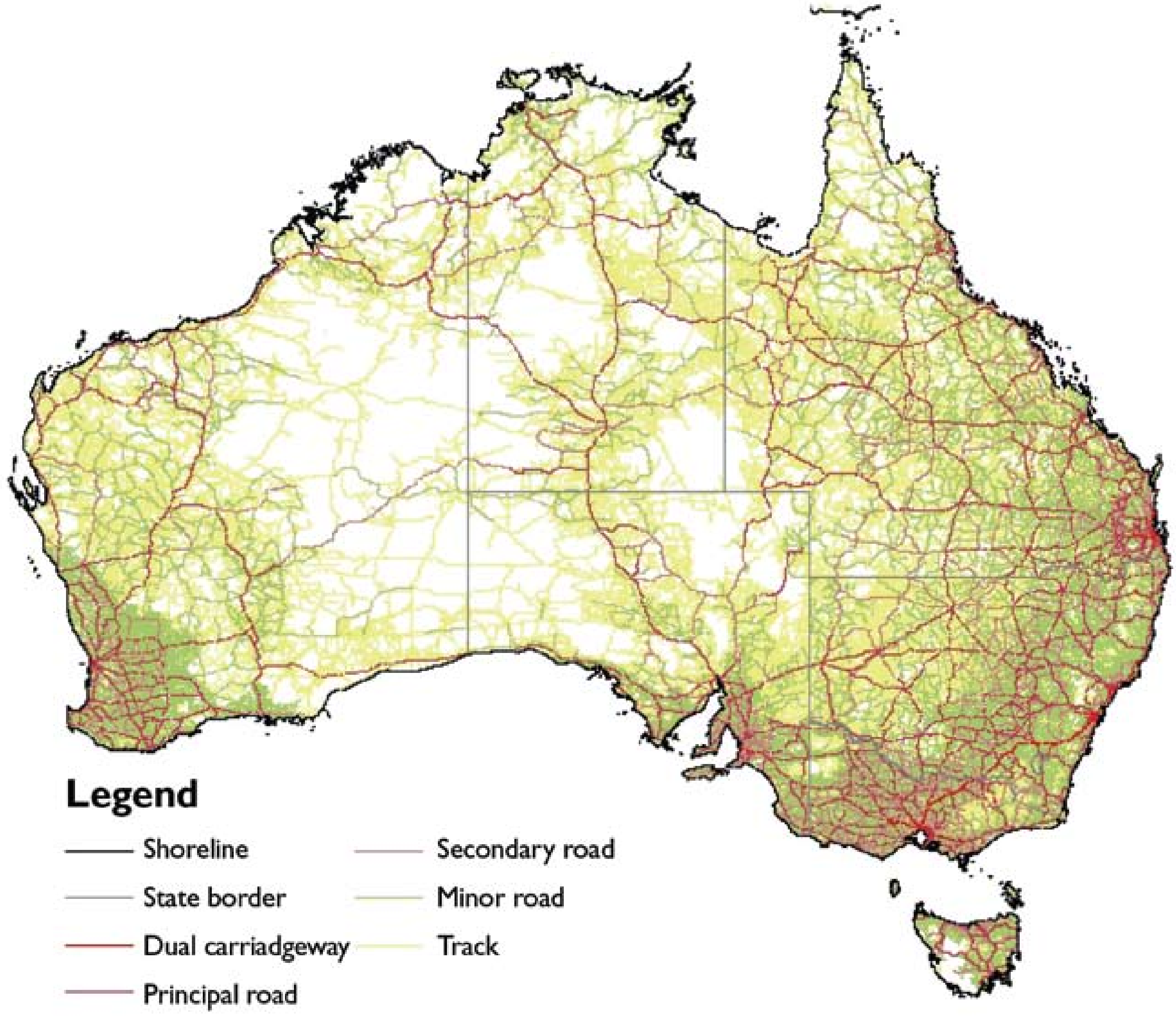

Figure 1. Australian road network. Source: Geoscience Australia, 2006.

A final major impediment to the development of strategic management frameworks for roads is the lack of information on the impacts of roads on a broad spectrum of wildlife. The majority of studies have been relatively specific and have concentrated on separate road effects on a subset of vertebrates, such as the barrier effects of roads on small mammals (Richardson *et al.* 1997; Goosem 2001; Rondinini and Doncaster 2002). Relatively few studies have investigated more than one of the potential effects of roads on a variety of vertebrate groups simultaneously (but see Jaeger *et al.* 2005; Ramp *et al.* 2005). A more comprehensive approach may enable management actions to be prioritised with regard to conservation importance, and may identify complex interactions between taxa relevant for broad-scale management.

This paper focuses on some of the effects of an arid-zone road on three vertebrate groups: kangaroos, small mammals and lizards. An arid ecosystem was chosen as studies conducted in arid ecosystems are few (Brooks and Lair 2005) yet arid ecosystems cover up to one third of the earth's land surface (Kinlaw 1999). We report on the impacts of an arid-zone road on kangaroo population demographics, on the species composition of kangaroo, small mammal and lizard communities, and on the abundance and sex ratios of two threatened small mammal species in New South Wales (NSW). This broad approach allowed us to determine which vertebrate populations and communities were negatively affected by an arid-zone road, and thus to determine which road effects should be prioritised for management. Informed management of arid-zone roads is of particular importance in Australia as approximately 70 % of the continent is arid (Stafford Smith and Morton 1990), and major trans-continental and arterial roads pass through arid areas (Fig. 1) that support a diverse endemic wildlife: Australia's arid zone has the highest reptile diversity in the world's arid zones (Pianka 1986; James and Shine 2000). Australia's arid zone also supports a diversity of small mammals, although many are now threatened following a wave of extinction with European settlement (Dickman *et al.* 1993). Any anthropogenic disturbance that could threaten the integrity of the arid ecosystem, the diversity of lizards, or further threaten the status of small mammals needs to be appropriately managed.

Methods

Study site

The study was conducted at the University of New South Wales Arid Zone Research Station, Fowlers Gap (31° 05' S, 141° 43' E), in north-western NSW, Australia. Fowlers Gap is located on the Silver City Highway approximately 110 km north of Broken Hill and covers an area of 38, 888 ha. The station is typical of Australia's southern sheep rangelands and is run as a working sheep station as well as a centre for research, teaching, and tourism. No commercial or non-commercial kangaroo shooting occurs on the station. The climate at Fowlers Gap is dry and mildly arid, with hot summers and mild winters. Mean annual rainfall is 238.5 mm and is erratically distributed throughout the year (coefficient of variation between 1966 and 2004 = 46.1 %); however, winter rains are generally more reliable than summer rains and have a greater impact on vegetation growth (Moss and Croft 1999). A 21.2 km bitumen section of the Silver City Highway (6 m in width) runs from the southwest boundary of the station through to its northeast boundary. The topography of Fowlers Gap is diverse: the western section of the station includes part of the Barrier Ranges (elevation 180-240 m), while the eastern section consists of alluvial floodplains (140-170 m) (Mabbutt 1973). Thus, the highway traverses areas of high relief where the dominant vegetation is low woody perennial shrubs (< 1 m) chiefly of the Chenopodiaceae family, and of low relief dominated by various tussock grasses (approximately 0.5 m; Burrell 1973).

Kangaroo population structure and density

Day (commencing at dawn) and night (2 h after sunset) counts of kangaroos were conducted weekly within 24 h of each other over 21 months between March 2003 and November 2004. Counts were conducted along two transects: one along the 21.2-km stretch of the Silver City Highway (road transect) and the other along a parallel 10 km dirt track located approximately 500 m from the highway in the floodplains (hinterland transect). The hinterland transect was designed to measure aspects of the kangaroo community in the same landscape unit but distant from the road and not a population independent of any road effects. Day and night counts were performed to obtain information about possible changes in kangaroo densities relative to distance from the road at different times of day, but day counts along the road most accurately estimated the species, size and sex composition of the source population, while night counts along the road estimated the numbers and species of kangaroos within the driver's field of view. This provided an index of the kangaroos that were at immediate risk of a kangaroo-vehicle collision. Data from the hinterland transect were compared to data from a 10 km parallel section of the road transect traversing the floodplains rather than data from the entire road transect.

Population densities were estimated using either a line or strip-transect method (Buckland *et al.* 2001). For day counts, the sighting angles (from a protractor) and radial distances (from a Bushnell 2000 laser rangefinder) of each kangaroo or the centre of a group of kangaroos from transects were estimated. Kangaroos were considered to belong to a group if they were in a cluster within 50 m of each other. The data were truncated to exclude the last 10% of distances and data were grouped into twenty-five 10-m intervals since pilot runs of the data revealed that the best models were achieved with this exclusion and data grouping. A hazard rate model with a cosine adjustment factor was fitted to the data (DISTANCE V4.0), with post-stratification by week and species. For night counts, the abundance of each kangaroo species within a fixed strip of 20 m width on either side of transects was estimated and the density was calculated from the area of the strip. Both day and night surveys were conducted by driving a standard vehicle (Nissan Navara single cab tray-top/pick-up) at about 25 km/h and scanning for kangaroos. Four species – Red kangaroos *Macropus rufus*, Euros M. *robustus erubescens*, Western grey kangaroos M. *fuliginosus* and Eastern grey kangaroos M. *giganteus* – were identified, but counts of the latter two species were pooled together due to the difficulty in quickly distinguishing these species, especially during the night. Individual kangaroos were not identified and so they may have been included more than once throughout the study; however, given that counts were conducted over relatively large spatial scales, pseudo-replication was likely to cause minimal bias (Oksanen 2004).

Kangaroo roadkill

Data for roadkilled kangaroos were collected over 21 months between February 2003 and November 2004. The highway was surveyed every second day from a standard vehicle travelling at 40 km/h. For each roadkill, the date, location (Garmin GPS II), species, and sex were recorded. When present and relatively undamaged, the heads of kangaroos were collected for an estimation of age by molar progression (after Kirkpatrick 1965). This method of aging kangaroos is not available for M. *fuliginosus*. However, as M. *fuliginosus* is closely related and the mainland subspecies has similar limb dimensions and growth to M. *giganteus* (Poole *et al.* 1984), the method for aging M. *giganteus* was used for aging M. *fuliginosus*.

Small mammals and lizards

Eight seasonal surveys of small mammals and lizards were conducted using pitfall traps over two years between July 2003 and April 2005. Ten sites were randomly selected along the highway, five in each of the hills and floodplain landscape types. At each site a pitfall unit was placed 10 m from each side of the road edge and in the hinterland (250 m from each side of the road edge; pitfall units oriented parallel to the road). The hinterland monitoring area was chosen on the basis that arid-zone small mammals are able to cover distances up to 200 m as part of their usual foraging/other activities (Read 1984). Pitfall units consisted of two pitfall traps buried flush to the ground, placed approximately 10 m apart and linked together by a drift fence. Traps were lengths of polyvinyl chloride stormwater pipe, 15 cm in diameter and 60 cm deep, fitted with galvanised steel bases. Drift fences were lengths of plastic weed mat that stood approximately 20 cm high after being partially buried.

Traps were checked twice a day at sunrise and from mid-afternoon. Captured animals were identified to species (after Strahan 1995, Cogger 1996 and Swan *et al.* 2004), sexed (small mammals only) and marked for identification by unique ear-notching for small mammals and nail polish for lizards. Trapping effort varied over the study, but mostly ran for ten days and nights per pitfall unit. Thus, small mammal and lizard abundance data were standardised for trapping effort by dividing their values by the number of trapping nights per pitfall unit in each season prior to analyses. The total number of trap nights was 2,800 from 40 pitfall units.

No attempt was made to collect information on small mammal and lizard mortality as a result of collisions with vehicles. This was largely due to the difficulty in detecting roadkilled individuals of these vertebrate groups from a moving vehicle, and the rapid removal of carcasses by predators.

Statistical analyses

Univariate GLM (SPSS for Windows V13.0) was used to examine how kangaroo densities at areas relative to the road (transects) varied between kangaroo species (M. *rufus*, grey kangaroos and M. *r. erubescens*). Other predictors included in the GLM were: time of day, total rainfall per week, average weekly traffic volume and various weather variables (reduced to weather components) as these are also likely to influence kangaroo densities or use of areas. Data for traffic and weather variables were collected as outlined in Lee *et al.* (2004) for post-drought data. Weather variables (eg. temperature, humidity, wind speed, barometric pressure and dewpoint) were reduced to components using principal component analysis as weather variables were highly correlated (PCA, SPSS for Windows V13.0). Examination of how kangaroo densities relative to the road varied according to age/sex was not possible as too many kangaroos, particularly grey kangaroos, could not be accurately identified into age/sex classes. Model terms were added into GLM using a stepwise technique, with all terms and interactions initially entered into models and dropped if not significant at $P < 0.05$. The final models were those which included terms for which elimination would have reduced the explanatory power of the models (Adjusted R^2 used, Quinn and Keough 2002). If significant interaction effects with transect and species were detected, differences between the levels of the interacting factors were tested for each species separately using one-factor Anova. Assumptions for GLM were checked by examining frequency histograms of standardised residuals with normal curves fitted, normal P-P plots of standardised residuals, and scatterplots of standardised residuals against the predicted standardised values of the dependent variables. Formal tests of normality and homogeneity were not used as these tests often reject null hypotheses of normality in situations when subsequent tests may be accurate (Quinn and Keough 2002). In addition, the homogeneity of regression slopes was checked by examining interactions between variables and factors separately (P should not be significant for these interactions). Checks for collinearity were made by examining Pearson's correlations (Quinn and Keough 2002).

Roadkill data were examined with chi-square tests to compare the proportions of species and sexes killed with their respective proportions in source populations, with landscape types considered separately. Exact tests with 10, 000 Monte Carlo simulations were used to account for the small sample size (SPSS for Windows V13.0). The numbers of M. *fuliginosus* and M. *giganteus* killed were pooled together for analyses as the two species were not distinguished from each other during kangaroo counts. In addition, only the sex frequencies for M. *rufus* and M. *r. erubescens* were compared as sex determination of grey kangaroos in the source population could not be accurately determined for males and females of similar size. Separate comparisons of the frequencies of species killed were made with their respective numbers in the source populations estimated during the day and night.

Small mammal data were averaged across seasons per pitfall unit prior to analyses as averages helped to dampen temporal variation in small mammal captures and statistical power would be lost if small mammal captures were partitioned into seasons. Data from seven seasons rather than eight were used in analyses (winter 2003 was excluded) since captures in this first season of trapping were anomalously low (two House mice *Mus domesticus* caught over five nights in 40 pitfall units), and believed to be influenced by the drought of 2002-2003. Data for lizards were not averaged across seasons due to the significant variations in captures between monitoring areas over time and high capture rates (winter 2003 was excluded from analysis). Distance-based multivariate tests that partitioned variance based on a distance measure and generated a multivariate analogue to Fisher's F-ratio with permutations used to calculate *P*-values, were used to determine if the species composition of small mammal and lizard communities varied between monitoring areas (road and hinterland) and according to landscape type (hills and floodplains) and season (two-factor design for small mammals, three-factor design for lizards) (PERMANOVA 1.6; Anderson 2005). Small mammal and lizard data were fourth-root transformed to put greater emphasis on intermediate and rarer species, Bray-Curtis distance measures were used, and 9, 999 permutations (see Anderson 2001) were performed to generate *P*-values.

Three-factor Anova (SPSS for Windows V13.0) were used to examine whether the abundances and sex ratios of *Sminthopsis macroura* and *Leggadina forresti* varied between monitoring areas and landscape types. Data where the sexes of individuals were unknown were excluded from analysis.

Results

Numbers of kangaroos counted and their densities relative to the road

A total of 3661 kangaroos was counted during the day (1407 along the road transect and 2254 along the hinterland transect) compared to 299 kangaroos counted during the night (151 along the road transect and 148 along the hinterland transect). Kangaroo densities averaged 3.5 ± 0.2 kangaroos km^{-2} along the road and 7.4 ± 0.5 kangaroos km^{-2} in the hinterland during the day compared to 4.7 ± 3.0 kangaroos km^{-2} along the road and 4.5 ± 1.7 kangaroos km^{-2} in the hinterland during the night (mean ± 95% confidence intervals).

Effects of the road on kangaroo species densities

The densities of kangaroos at areas relative to the road varied among species ($F_{(2,893)} = 46.54$, $P < 0.001$). *Macropus rufus* and *M. r. erubescens* densities were higher along the hinterland transect compared to the road transect (*M. rufus*: $F_{(1,308)} = 56.01$, $P < 0.001$; *M. r. erubescens*: $F_{(1,308)} = 8.48$, $P = 0.004$), while grey kangaroo densities were higher along the road transect compared to the hinterland transect ($F_{(1,308)} = 8.86$, $P = 0.003$).

The densities of kangaroo species at areas relative to the road also varied depending on time of day ($F_{(5,893)} = 13.53$, $P < 0.001$). Grey kangaroo densities were higher during the day than the night along both transects (road: $F_{(1,153)} = 34.78$, $P < 0.001$, hinterland: $F_{(1,153)} = 19.42$, $P < 0.001$). Similarly, *M. rufus* densities along the hinterland transect were higher during the day than the night ($F_{(1,153)} = 27.95$, $P < 0.001$). However, along the road transect, *M. rufus* densities were higher during the night than the day (difference not significant: $F_{(1,153)} = 0.07$, $P = 0.797$). *Macropus r. erubescens* displayed no density differences between times of day along transects (road: $F_{(1,153)} = 0.71$, $P = 0.402$, hinterland: $F_{(1,153)} = 0.034$, $P = 0.855$) (Fig. 2).

The densities of kangaroo species at areas relative to the road varied depending on rain ($F_{(5,893)} = 2.63$, $P = 0.022$). Densities of all kangaroo species were

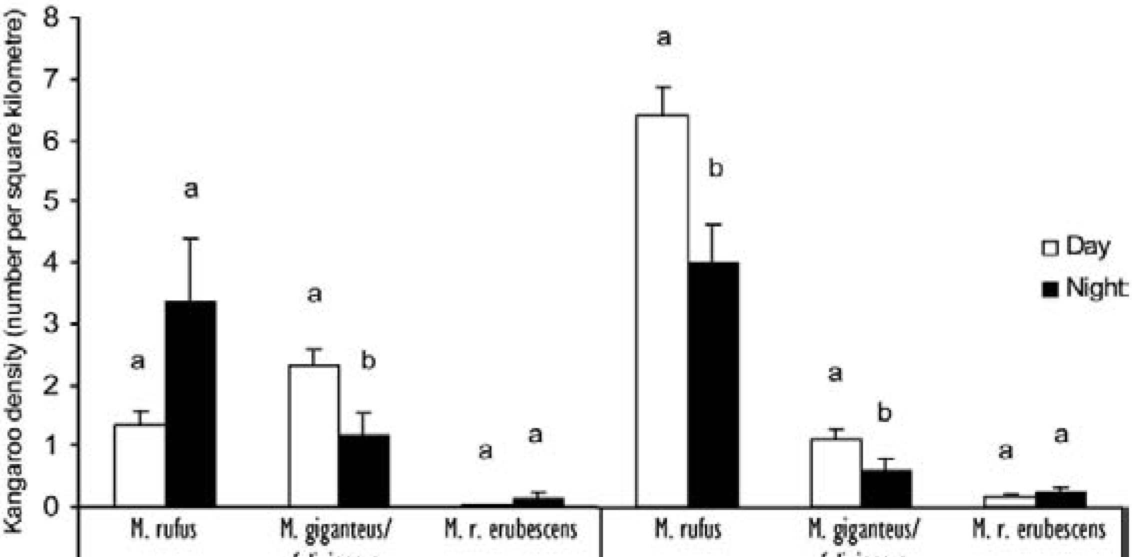

Figure 2. Mean densities per kangaroo species (+ 1 SE) along the road and hinterland transects during the day and night. Letters denote significant differences between times of day for each species along the two transects. Results are from separate one-factor Anova for each species between times of day along road and hinterland transects that followed significant results for species*transect*time of day interactions.

higher when no rain fell over the last 2 weeks in the hinterland (differences were significant for *M. rufus* and grey kangaroos; *M. rufus*: $F_{(1,153)} = 7.67$, $P = 0.006$, grey kangaroos: $F_{(1,153)} = 4.53$, $P = 0.035$; trend for significant differences for *M. r. erubescens*: $F_{(1,153)} = 3.34$, $P = 0.07$). Conversely, along the road, densities of all kangaroo species were higher when rain fell over the last 2 weeks (differences not significant; *M. rufus*: $F_{(1,153)} = 0.28$, $P = 0.599$, grey kangaroos: $F_{(1,153)} = 0.47$, $P = 0.495$; *M. r. erubescens*: $F_{(1,153)} = 0.37$, $P = 0.545$).

Numbers, species, sex and age of roadkill

A total of 92 roadkilled kangaroos were found during the study period which averaged 4.4 kills per month (0.007 roadkills day^{-1} km^{-1}). Kills usually occurred during night-time hours. *Macropus rufus* made up the majority of kills, followed by *M. fuliginosus*, *M. r. erubescens* and *M. giganteus* (Table 1). Kills of *M. rufus* and *M. fuliginosus* were divided equally between sexes. In contrast, more males were killed compared to females among *M. giganteus* and *M. r. erubescens* (Table 1).

Roadkilled kangaroos were aged between 1 and 10 years (median = 2, mode = 1, n = 65). When examined per species, roadkilled *M. rufus* and *M. fuliginosus* were mostly young individuals, with 83 % and 71 % of all *M. rufus* and *M. fuliginosus* (n = 34 and n = 27 for roadkilled individuals of known age, respectively) aged between one and three years (*M. rufus*: 56 %, 21 % and 6 %; *M. fuliginosus*: 26 %, 30% and 15 % for ages one, two and three years). Roadkilled *M. r. erubescens* were aged 3 and 4 years (25 % and 75%, respectively), although only 4 individuals could be aged. Ages of roadkilled *M. giganteus* were unknown.

Effects of roadkill on kangaroo population demographics

No sex biases were found for *M. rufus* or *M. r. erubescens* when compared to the respective proportions of sexes in the source populations in the hills and floodplains (*M. rufus*: hills: $\chi^2 = 1.53$, df = 1, $P = 1$; floodplains: $\chi^2 = 1.68$, df = 1, $P = 0.301$; *M. r. erubescens*: hills: $\chi^2 = 3.18$, df = 1, $P = 0.455$; floodplains: observed and expected values equal). However, the number of roadkilled male *M. rufus* appeared higher than females in the female-dominated floodplains habitat (males: observed = 17, expected = 12; females: observed = 13, expected = 18). The pyramidal age distributions of kangaroo populations observed in studies conducted by Russell (1971) and Norbury *et al.* (1994) were reflected in the age distributions of roadkilled kangaroos.

Effects of roadkill on kangaroo community compositions

Kangaroo species were killed in similar proportions to their estimated proportion of the daytime population in the hills habitat ($\chi^2 = 4.26$, df = 2, $P = 0.154$), but fewer grey kangaroos and more *M. rufus* and *M. r. erubescens* were killed than expected in the floodplains habitat ($\chi^2 = 6.85$, df = 2, $P = 0.033$; grey kangaroos: observed: 33, expected: 46; *M. rufus*: observed: 37, expected: 26; *M. r. erubescens*: observed: 2, expected: 0). There were no significant differences in the proportions of species killed to their estimated proportion in the night-time population, although a similar trend for less grey kangaroos and more *M. rufus* killed was again found in the floodplains (hills: $\chi^2 = 0.14$, df = 2, $P = 1$; floodplains: $\chi^2 = 6.05$, df = 2, $P = 0.079$, grey kangaroos: observed: 33, expected: 19; *M. rufus*: observed: 37, expected: 51; *M. r. erubescens*: observed: 2, expected: 2).

Small mammal captures

A total of 192 small mammals from seven species were caught over the study. *Sminthopsis macroura* was the most abundant species (28.6 % of all captures) followed by Fat-tailed dunnarts *S. crassicaudata* (27.1 %), *M. domesticus* (23.4 %) and *L. forresti* (16.7 %) (Table 2).

Effects of the road on small mammal community compositions

Differences in small mammal communities existed between monitoring areas ($F_{(1,36)} = 3.81$, $P = 0.025$) but there were no differences in small mammal communities for landscape type*monitoring area interactions ($F_{(1,36)} = 2.12$, $P = 0.146$). *Sminthopsis macroura* and *L. forresti* abundances were lower and *M. domesticus* and *S. crassicaudata* abundances were higher at the road edge compared to their abundances in the hinterland (Fig. 3).

Effects of the road on abundance and sex ratios of threatened small mammal species

Sminthopsis macroura abundance was significantly lower at the road edge compared to in hinterland areas ($F_{(1,72)} = 8.63$, $P = 0.004$; mean abundance per sampling night at road = 0.006 ± 0.01, hinterland = 0.014 ± 0.016), but lower abundances at the road edge compared to hinterland areas were not significant for *L. forresti* ($F_{(1,72)} = 0.58$, $P = 0.448$; road = 0.004 ± 0.008, hinterland = 0.008 ± 0.021). More females were caught overall for *L. forresti* compared with males ($F_{(1,72)} = 15.01$, $P < 0.001$;

Table 1. Percentage of kangaroo species killed and percentage composition of males and females killed per species between February 2003 and November 2004.

Species	Total (n = 92)	* Females (n = 35)	* Males (n = 42)
Macropus rufus	48	50	50
M. fuliginosus	39	53	47
M. giganteus	4	25	75
M. robustus erubescens	9	0	100

* Excludes individuals where sex was indeterminate due to condition of carcass (n = 15).

Table 2. Small mammals caught between spring 2003 and summer 2005.

Scientific name	Common name	Numbers captured	Percentage of captures
Sminthopsis crassicaudata	Fat-tailed Dunnart	52	27.1
Sminthopsis macroura	Stripe-faced Dunnart	55	28.6
Planigale tenuirostris	Narrow-nosed Planigale	6	3.1
Planigale gilesi	Giles' Planigale	1	0.5
Leggadina forresti	Forrest's Mouse	32	16.7
Pseudomys hermannsburgensis	Sandy Inland Mouse	1	0.5
Mus domesticus	House Mouse	45	23.4

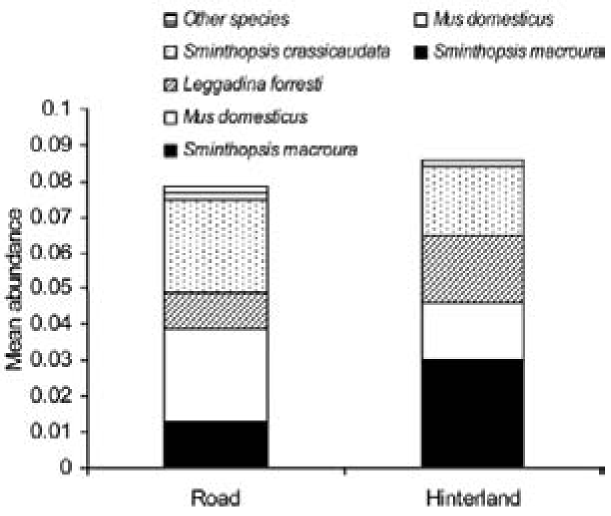

Figure 3. Mean abundance of small mammals per sampling night at road and hinterland monitoring areas between spring 2003 and summer 2005.

mean abundance of females per sampling night = 0.011 ± 0.021, males = 0.002 ± 0.006), and while this pattern was also observed for *S. macroura* (females = 0.012 ± 0.015, males = 0.009 ± 0.012) differences in sex ratios were not significant ($F_{(1,72)}$ = 1.08, P = 0.301). Female dominance was consistent at monitoring areas relative to the road for both the threatened small mammal species: there were no monitoring area*sex interactions or landscape type*monitoring area*sex interactions (*L. forresti*: $F_{(1,72)}$ = 0.17, P = 0.685 and $F_{(1,72)}$ = 0.08, P = 0.782; *S. macroura*: $F_{(1,72)}$ = 0.14, P = 0.714 and $F_{(1,72)}$ = 0.10, P = 0.753, respectively).

Lizard captures

A total of 306 lizards from 17 species were caught over the study. The Lined earless dragon *Tympanocryptis lineata* was the most abundant species (33.3 % of all captures) followed by Barred wedgesnout ctenotus *Ctenotus schomburgkii* (24.2 %) Leonhardi's ctenotus *C. leonharidii* (11.1 %), Bynoe's gecko *Heterontia binoei* (9.5 %) and *C. uber* (4.9 %) (Table 3).

Table 3. Lizards caught between spring 2003 and summer 2005.

Scientific name	Common name	Numbers captured	Percentage of captures
Ctenotus leonhardii	Leonhardi's Ctenotus	34	11.1
Ctenotus schomburgkii	Barred Wedgesnout Ctenotus	74	24.2
Ctenotus strauchii	Eastern Wedgesnout Ctenotus	6	2.0
Ctenotus uber	Spotted Ctenotus	15	4.9
Lerista punctatovittata	Spotted Lerista	1	0.3
Menetia greyii	Grey's skink	14	4.6
Diplodactylus byrnie	Gibber Gecko	7	2.3
Diplodactylus tessalatus	Tessellated Gecko	2	0.7
Heterontia binoei	Bynoe's Gecko	29	9.5
Underwoodisaurus milii	Thick-tailed Gecko	1	0.3
Ctenophorus nuchalis	Central Netted Dragon	6	2.0
Tympanocryptus lineata	Lined Earless Dragon	102	33.3
Tympanocryptus tetraporaphora	Long-tailed Earless Dragon	10	3.3
Morethia adelaidensis	Chenopod Morethia	2	0.7
Morethia boulengeri	Boulenger's Morethia	1	0.3
Trachydosaurus rugosus	Shingleback	1	0.3
Varanus gouldii	Gould's Goanna	1	0.3

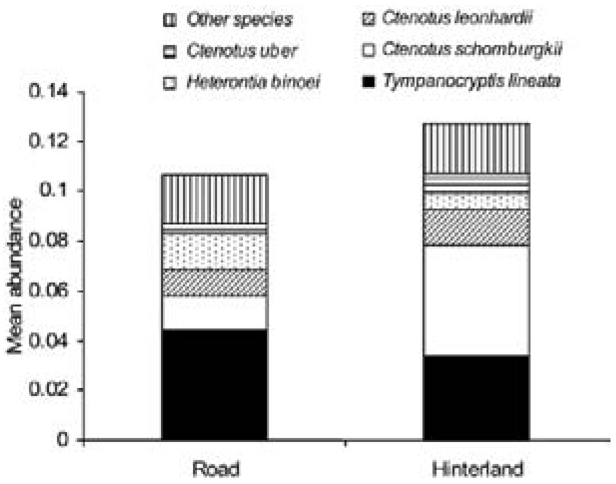

Figure 4. Mean abundance of lizards per sampling night at road and hinterland monitoring areas between spring 2003 and summer 2005.

Effects of the road on lizard community compositions

Differences in lizard communities existed between monitoring areas ($F_{(1,144)} = 5.57$, $P = 0.001$) but there were no differences in lizard communities for interactions with monitoring area (landscape type*monitoring area: $F_{(1,144)} = 1.15$, $P = 0.312$; season*monitoring area: $F_{(3,144)} = 0.88$, $P = 0.543$; season*landscape type*monitoring area: $F_{(3,144)} = 1.13$, $P = 0.320$). Species that had low abundances at the road edge compared to in hinterland areas were mostly *Ctenotus* species. In contrast, species that had high abundances at the road edge compared to in hinterland areas included dragon and gecko species (Fig. 4).

Discussion

Many of the road effects that we found in this study were likely due to the highway enriching food resources and altering microhabitats in its immediate vicinity. Arid-zone roads enrich the quality of vegetation at their edges by shedding water from their surfaces to these areas, thereby providing a resource normally limiting in arid ecosystems (Lightfoot and Whitford 1991; Norton and Stafford Smith 1999; Appendix 1). Arid-zone roads also alter microhabitats around them through the creation of open space, increases in surface temperatures, disruption to soil profiles and removal of soil crusts (Lee 2006). Vertebrates in arid ecosystems generally distribute themselves in their preferred food resource and habitat/microhabitat "patches" (Stafford Smith and Morton 1990). Thus, higher M. *rufus* densities at the road during the night compared to the day, and higher kangaroo densities overall at the road 2 weeks after rain compared to areas further from the road most likely reflected their movements for food. Differences in overall kangaroo densities and small mammal and lizard abundances at areas relative to the road probably reflected their preferences for particular habitats and microhabitats. Kangaroo roadkill is often a consequence of changes in kangaroo abundances relative to the road (Coulson 1989; Lee 2006); thus, as kangaroo densities may have been influenced by food availability around the road, the frequency of kangaroo roadkill was also likely to be affected by changes in food availability around the road.

Of the kangaroo species, only M. *rufus* had higher densities at the road during the night compared with during the day. This is probably because M. *rufus* has a highly selective diet (Dawson and Ellis 1994; Moss and Croft 1999), and will move to areas where preferred forage is available consistent with the higher quality forage (grasses and forbs) Lee (2006) found at the road compared with further from the road. In contrast, grey kangaroos, particularly M. *fuliginosus*, are more generalist in their diets and are able to take in browse in addition to pasture (Barker 1987). However, it is possible that grey kangaroos were less detectable than other species at the road during the night. Grey kangaroos merge more into a dark background compared with light fronted M. *rufus*, and depressions at the sides of the road may have further obscured them at night. Further, all kangaroo species displayed higher densities at the road 2 weeks after rain where the impermeable road surface shed more water to adjacent vegetation, promoting its growth, compared with areas further from the road without extra water. Still, kangaroos usually separate their diurnal resting from nocturnal foraging sites (M. *rufus*: Watson and Dawson, 1993; M. *giganteus*: Southwell, 1987; M. *fuliginosus*: Coulson, 1993; M. *r. erubescens*: Croft, 1991) and so our results most likely reflect real differences in densities of different species proximal to the road during the night.

There was strong evidence that the differences in the overall densities of kangaroos and abundances of small mammals and lizards at areas relative to the road reflected the habitat preferences of each species since the occurrence of high densities and abundances of species were consistent with their preferred habitats. The road in our study passed through an area of shrub (mostly *Senna* species) which was not present at areas further from the road. Lower densities of M. *rufus* and higher densities of grey kangaroos at the road compared to areas further from the road reflect these species' respective preferences for open areas and areas with more shrub cover (Dawson 1995). The study road also changed microhabitats in its vicinity through changes in soil structure and vegetation composition (Lee 2006). Thus, at the microhabitat scale, areas near the road were more open than areas further from the road, with less perennial grasses (eg. *Astrebla* spp.) and less perennial shrubs, such as bluebushes (eg. *Maireana* spp.) and saltbushes (eg. *Atriplex*, *Rhagodia* and *Chenopodium* spp.). Lower *S. macroura* and low *L. forresti* abundances at the road compared to areas further from the road reflect these species' preference for microhabitats with high vegetation cover, particularly cover provided by tussock grassland (Dickman *et al.* 1993; Morton 1995a; Reid and Morton 1995) that possibly enhance food supplies (Frank and Soderquist 2005). High M. *domesticus* and *S. crassicaudata* abundances at the road compared to areas further from the road are compatible with M. *domesticus*' tendency to inhabit disturbed areas (Singleton 1995) and both species' tendency to forage on bare, open areas (Fox and Pople 1984; Dickman 1994; Morton

1995b; Frank and Soderquist 2005). Moreover, low skink abundances and high gecko and dragon abundances at the road compared to areas further from the road reflect the greater tolerances of geckos and dragons for high temperatures and their greater ability to thermoregulate than skinks (Heatwole and Taylor 1987; MacMillen *et al.* 1989; Henle 1990).

The effect of the study road in changing microhabitats only extended a short distance from the road edge. At this site, Lee (2006) found that changes in vegetation and soil extended to approximately 10 m from the road. These changes were reflected in the quality of various plant groups (such as grasses, forbs and copperburrs – mostly *Sclerolaena sp.*) and the amount of water in the soil. The quality of plant groups and amount of water in the soil were significantly higher at the road edge compared with areas 10 m, 50 m and 250 m away from the road edge. As such, it is likely that the changes in species composition of vertebrate communities by the road were local in scale. Larger-scale effects which could compromise the integrity of vertebrate communities probably would not occur unless the density of arid-zone roads increased.

Kangaroo species were killed in similar proportions to their species proportions in the source population along the study road, and no biases were found for the proportions of sexes killed to their sex proportions in source populations of M. *rufus* and M. *r. erubescens*. In addition, most roadkilled kangaroos were young individuals. Roadkill was thus a general reflection of kangaroo populations adjacent to the road, which in turn reflected the species distributions relative to the road based on food and habitat preferences. However, some care should be taken when interpreting these results. Depending on day or night estimates of populations, we found significantly more, or trends for more, M. *rufus* and M. *r. erubescens* and less grey kangaroos were killed than expected according to their proportions in the source population where the study road traversed floodplains. We also found a high proportion of male M. *rufus* killed in a female-dominated population and, although no sex biases were found for M. *r. erubescens*, males of this species may have been selectively killed due to their being present around roads more so than females (Lee 2006). These results suggest that some kangaroo species and sexes are killed disproportionately. Assuming that populations are not replenished by the movement of individuals to the area from further afield, disproportionate kills could lead to changes in kangaroo community compositions and population demographics near the road.

A possible reason for the potentially higher susceptibility of M. *rufus* to being killed compared to other kangaroo species could lie in the fact that M. *rufus* is more reactive (flighty) to approaching vehicles than the other species (Lee 2006). This greater level of flightiness may increase the chances of a collision occurring as it increases the chances of individuals being in the path of oncoming vehicles. Similarly, a greater level of flightiness in young individuals (Banks 2001) may have contributed to the higher numbers of young rather than older individuals killed. Higher kills of male M. *rufus* and M. *r. erubescens* may be due to their riskier behaviours compared to females (Arnold *et al.* 1994), or their wider movement patterns compared to females (Norbury *et al.* 1994; Clancy 1989). Even so, biases towards M. *rufus* and M. *r. erubescens*, particularly males of these species, as well as towards young individuals, may not necessarily have a significant impact on kangaroo community composition and population viability and health. This is because M. *rufus* has a greater ability to reproduce in good conditions compared with grey kangaroos: the more common of the grey kangaroo species in the area, M. *fuliginosus*, lack embryonic diapause, generally breed on a seasonal basis, and have young-at-foot that remain with their mothers for longer periods of time compared to M. *rufus* and M. *r. erubsecens* (Dawson 1995). The slight bias towards M. *rufus* being roadkilled is probably easily offset by the rapid replacement of individuals within their population. Further, selective male and juvenile mortality in kangaroo populations may reduce genetic variation and reproductive success if there are fewer males or young individuals left in populations. However, males in sexually dimorphic species typically have higher mortality rates and lower life expectancy than females, as do juveniles compared to adults (Clutton-Brock *et al.* 1985) and there are likely to be surplus breeding males (Clancy and Croft 1992) and juveniles in kangaroo populations.

Management priorities

In our study, no vertebrate groups or threatened species appeared vulnerable to the effects of the Silver City Highway, at least at the population level. Changes caused by the road to vertebrate communities were likely to be local rather than regional. Thus, taxa need not be prioritised in order of conservation importance for the management of road effects in this instance.

However, a strategic management option for arid-zone roads may lie in reducing kangaroo roadkill frequency through restoring the natural integrity of vegetation adjacent to arid-zone roads. Such a management strategy could simultaneously reduce other negative effects of arid-zone roads on vertebrate groups and benefit the conservation of species that may be threatened. For example, this management strategy could 1) reduce the likelihood of secondary roadkill for other vertebrate taxa scavenging on carcasses, 2) reduce the likelihood of human injuries from collisions with the largest (native) vertebrates, the kangaroos; and 3) minimise the localised effects that arid-zone roads have on the composition of small mammal and lizard communities.

As discussed earlier, kangaroos, particularly M. *rufus*, are attracted to roadside areas during their active foraging periods. Removal of high quality forage through the replacement with shrubs and unpalatable vegetation (eg. saltbushes and bluebushes) could remove the incentive for kangaroos to approach arid-zone roads and reduce their susceptibility to collisions with vehicles. Furthermore, the strategy of encouraging the growth of shrubs at arid-zone roadsides could reduce the effects of arid-zone roads on small mammal and lizard communities. Shrubs growing near roads would reduce microhabitat differences currently experienced along arid-zone roads relative to areas further away from roads and thus reduce heterogeneity and discontinuity in habitat driving community differences.

Encouragement of low shrubs along roadsides may not meet road safety concerns as management of arid-zone roads aims to increase visibility and reduce obstacles along verges should a driver have to pull off the road in an emergency. However, greater risk to vehicle occupants is likely to result from collisions with large animals than from being unable to pull off roads. Therefore, management should be directed towards reductions in roadkill frequency in order to decrease the likelihood of human injuries from collisions or sudden evasive actions.

A reduction in the frequency of roadkill should lead to a reduction in the likelihood of secondary roadkill occurring on arid-zone roads. Roadkilled kangaroos can attract scavenging animals such as birds of prey to the road (Lee, *unpublished data*). While some species like Corvids exhibit behaviour that reduce their chances of being hit by vehicles (Choi 2004), other species, such as Wedge-tailed eagles *Aquila audax*, often remain at carcasses, probably to avoid expending energy in taking flight while heavy with food.

The best way to reduce roadkill is to reduce the presence of animals on the road or verge with the least compromise to the integrity of the original roadside habitat. Post road-construction habitat modification like we are suggesting has the benefit of mitigating roadkill frequency with large mammals while discouraging smaller vertebrates that tend to forage in open habitat. The latter behaviour is likely to cause them to stray onto the road surface where they are run over. However, management needs to take an integrative whole of community approach recognising that road construction and operation may favour some species over others, create a habitat sink caused by the high mortality of individuals drawn to the road, or fragment populations. Arid-zone roads probably do not completely restrict movement across them when roads are relatively narrow (Garland and Bradley 1984; Lee 2006) since the cover of vegetation in the arid zone is typically sparse and arid-zone animals are adapted to traversing open spaces and moving between preferred microhabitat patches (Dickman *et al.* 1995). However, caution needs to be taken about populations of small animals becoming fragmented if traffic volume and type warrants multi-lane roads or very wide cleared verges.

We need to recognise that a road through the arid rangelands causes a new linear enriched patch but has little effect in fragmenting an already open landscape unlike forested environments. Large animals whether wildlife or livestock will readily traverse the road and be an ever-present danger to motorists. The road verge can be made a less attractive place to dwell but ultimately driver awareness and behaviour govern the interaction when unpredictable flight patterns bring wildlife too close for comfort.

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APPENDIX I

Section of the Silver City Highway illustrating enhanced vegetation at the road edge and a roadkilled *Macropus rufus.*

Photo: E. Lee