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Assessing the impacts of roads in peri-urban reserves: Road-based fatalities and road usage by wildlife in the Royal National Park, New South Wales, Australia

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A B S T R A C T

For protected reserves set aside for conservation, the impact of roads and traffic on wildlife can be severe, particularly for those in the peri-urban environment. Often reserves possess many sealed roads that have regular traffic from tourists and local residents. As managerial bodies struggle to control the wide variety of threats to the fauna within these reserves, the loss of life on roads only compounds the precarious nature of wildlife survival in these disturbed environments. As a first step to addressing this concern in Australia, this study quantifies the fatalities of wildlife killed on roads within the Royal National Park in New South Wales, and estimates those wildlife species using roadside habitat in order to identify species susceptible to collisions. Modelling of fatality data indicated that mammals were most likely to be killed where forage was abundant on the roadside verge and where there was plenty of protective cover, while birds were most likely to be killed when the height of roadside vegetation was low. A number of collision hotspots were identified along the surveyed road that should be the target of mitigation efforts. The average speed of vehicles travelling within the park peaked at night. This is of particular concern as activity by Australian mammals tends to be greatest at night. The findings indicate that roads in peri-urban reserves have the potential to alter the movement of animals and impact on their populations through loss of life.

1. Introduction

Recognition of the deleterious impacts of roads has prompted a range of interest in the last few years (Sherwood et al., 2002; Forman et al., 2003). The impact of roads on wildlife can be pervasive as roads can cause numerous fatalities as a result of collisions with the vehicles that travel on them (Malo et al., 2004; Saeki and Macdonald, 2004; Ramp et al., 2005). Roads can also fragment populations by forming barriers to movement, isolating them from resources and mates (Richardson et al., 1997; Gerlach and Musolf, 2000). These impacts raise serious concerns about the stability and sustainability of roadside wildlife populations in road-affected environments, especially as the amount of transported goods and the number of people travelling on roads increases world-wide.

The ecological impact of roads on wildlife and habitat can be felt far from the road edge (Reijnen et al., 1995; Forman, 2000). This area of impact can be thought of as the 'road environment', often also termed the 'road effect zone' (Forman and Alexander, 1998). While the impact of major highways bisecting large conservation reserves has received considerable attention (Clevenger et al., 2003; Clevenger and Waltho, 2005), fauna living within conservation reserves that border areas of high human and road density are also under consid-

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erable threat. In the peri-urban environment, wildlife are often restricted to living within reserves set aside for wildlife conservation. The park and reserve system within the peri-urban environment is touted as a haven for wildlife, however, the impacts of roads can be prevalent in these environments (Lunney et al., 2002; Banks, 2004; Lopez, 2004). Although these reserves provide refuge for many wildlife species they typically have high visitation rates from tourists and in some cases contain townships within their borders. As a consequence, peri-urban reserves often contain many sealed roads that have regular traffic. As managerial bodies struggle to control the wide variety of threats to the fauna (and flora) within these reserves, such as feral predators and competitors, pollution and fire, the loss of life and fragmentation associated with roads only compounds the precarious nature of these wildlife populations.

Pertinent questions for those seeking to conserve these populations are how species are using the road environment and what factors are contributing to wildlife being involved in collisions with vehicles. Use of the road environment is typically species specific, with many animals completely avoiding the roads and others being attracted to it (Forman and Alexander, 1998; Forman et al., 2003). Population densities of birds in grasslands in The Netherlands have been shown to be adversely affected by the road environment, with declines in density and breeding habitat quality with increasing proximity to roads and highways by a range of species (Reijnen and Foppen, 1994; Reijnen et al., 1996). However, the road environment can provide a conduit for movement, facilitating easy access among habitats. That predator species exploit the road environment in this way has been previously well documented (Bennett, 1991), as many predator species, such as red foxes (*Vulpes vulpes*), use roads and other linear clearings like fire breaks and powerline clearings to hunt prey (May and Norton, 1996). While many small mammal species typically engage in crypsis and avoid open areas like roads, such as the fawn-footed Melomys (*Melomys cervinipes*) (Goosem, 2001), some like the meadow vole (*Microtus pennsylvanicus*) are also known to disperse along road corridors (Getz et al., 1978). The road environment can also provide many species with access to resources such as food and water. Kangaroos (*Macropus* spp.) are often attracted to roadside verges to forage, as the vegetation is often greener and of higher quality than in the surrounding areas (Bennett, 1991), while moose can sometimes be attracted to the salt used to reduce ice on highways (Fraser and Thomas, 1982). For established roads, those species that are susceptible to collisions with vehicles are, by definition, those that utilise the road environment. It is entirely probable, however, that species that exhibit aversive responses, or species that are highly susceptible to collisions, were once present in these areas.

However, use of the road environment on its own is not necessarily a good indicator of the likelihood of the susceptibility of a particular species to collisions with vehicles. There may be many reasons why, given species-specific behavioural characteristics and landscape attributes, a species may be susceptible to collisions. Indeed, Forman et al. (2003) cite a range of factors that make species vulnerable to road fatalities, such as mobility, habitat specificity, reproductive rate, resource needs and space use. It therefore follows that the determination of those explanatory factors contributing to fatalities should provide conservation managers with the knowledge to reduce collision rates (Seiler, 2003; Saeki and Macdonald, 2004; Ramp et al., 2005; Seiler, 2005). The collision between wildlife and vehicles is likely to be related to three sets of factors that include both spatial and temporal components. The first set relate to the likelihood of the presence of an animal on the road. Animal presence is often highly correlated with habitat and topographic features, along with the proximity to resources, road features like width, curvature, and surface type, as well as temporal fluctuation in population parameters like density, breeding and dispersal events and variation in climatic conditions. The second set of factors relate to the likelihood of a vehicle being present. The presence of a vehicle will vary with traffic volume, the proximity to human habitation and temporal variation due to the season, the day of the week and the time of day. While the presence of both an animal and a vehicle are necessary for a collision, the likelihood of a collision occurring will be influenced by road features like curvature and driver visibility, the time of day (tiredness of the driver), and the reason for the animal being on the roadside in the first place (i.e., foraging on the verge or actually trying to cross the road).

The answers to these questions will enable wildlife managers to address which species are susceptible to fatalities and identify what aspects of the road environment are contributing to loss of animal life on roads. To ascertain how wildlife survives in and uses road-affected reserves, this study focuses on one of Australia's premiere peri-urban reserves, the Royal National Park. As the second oldest national park in the world (established in 1879), the geographic proximity of the Royal National Park to Australia's largest city (Sydney, population 4.2 million) presents an interesting conundrum for managers trying to protect the flora and fauna of the park while also providing recreation to 1.25 million visitors per year and residence to over 2000 people. The transportation of both visitors and residents along sealed roads within the park is a necessary component of the park's existence. Residents are only able to access their homes by ferry (only operational during daylight hours) or via at least 22 km of sealed road (speed limit mostly 60–80 km/h). The park has a number of ongoing managerial issues, including red fox (*Vulpes vulpes*) control, control of introduced rusa deer (*Cervus timorensis*), the prevention of large wildfires and the management of human disturbance (New South Wales National Parks and Wildlife Servic, 2000). On top of this, park management has recently identified the need to quantify the impact of the road system on the long-term viability of wildlife populations in order to facilitate the development of appropriate conservation strategies aimed at maintaining park biodiversity.

To assess how the road environment affects wildlife within this peri-urban reserve, this study was conducted to: (a) quantify the use of the roadside verge by wildlife and identify species that make regular use of the roads; (b) to quantify road-based fatalities along a portion of the road system within the park; (c) to identify hotspots ('blackspots') of collisions to provide a target for future mitigation efforts; (d) to develop predictive models of road-based fatalities to identify explanatory variables influencing the likelihood of collisions.

2. Methods

2.1. Study area

The Royal National Park (34°05′S, 151°05°E) is located 32 km south of the Sydney central business district, New South Wales, Australia. It covers approximately 16,000 ha and has a wide diversity of habitats including heathland, woodland, eucalypt forest, rainforest, wetland and swamps (New South Wales National Parks and Wildlife Servic, 2000). The climate is temperate, where average day-time temperatures range from around 7° to 17° in the coolest month of July, to 18–26° in the warmest month of January. Average rainfall is highest (126 mm) in June and lowest (62 mm) in September (recorded at Sydney Airport by the Australian Bureau of Meteorology). The park is home to more than 50 mammal species (43 native), including a range of bats, possums, rats, dasyurids, echidna, wombats, gliders, marine mammals and feral mammals (New South Wales National Parks and Wildlife Servic, 2000). Surprisingly, the only macropodid present is the swamp wallaby (*Wallabia bicolor*). The bird life is diverse with 241 listed species, and includes a number of vulnerable and endangered species. There are roughly 40 species of reptile and 30 species of amphibian.

2.2. Fatality survey

This study focused on the most popular commuter route in the park. Surveys were conducted from the northern exit of Farnell Avenue at the Pacific Highway, which then becomes Audley Road, followed by Sir Bertram Stevens Drive. The surveys continued along Bundeena Drive all the way to the Bundeena Township. The stretch is approximately 22 km long, entirely sealed (bitumen) and consists of a single-lane in either direction. It includes speed zones of 50, 60 and 80 km/h although recommended speeds are as low as 25 km/h in places. Traffic volume is comprised mostly of local residents, visitors to the park and Bundeena Township, and New South Wales National Parks and Wildlife Service staff.

The 22-km stretch of sealed road was driven daily between 10th April and 31st August 2003. Driving was conducted at 20 km/h below the recommended speed limit as this provided an adequate trade-off between the efficacy of carcass identification and driver safety (Slater, 2002). Both driver and passenger searched the left-hand side of the road and its verge for any vertebrate fatalities, traversing the 22-km road in both directions. For each fatality observed, the location using a Garmin GPSII Plus unit was marked, noting the species, the most likely date of death (diurnal animals were assumed to have died on the day they were found, while the death date of nocturnal animals was adjusted to the previous day), the sex and age class (juvenile or adult) where possible, the type of injury and the presence of pouch young (for marsupials). Once details of the fatality were recorded the carcass was moved out of sight of the road so as to avoid double counting. In addition, park staff were informed of the research and were instructed to leave carcasses untouched.

At each collision location, vegetation height, canopy cover and understorey density were recorded at a point 5 m from the road verge on either side of the road. Vegetation height was estimated to the nearest metre. Understorey density was estimated at 0%, 25%, 50%, 75% or 100% dense, where percentages referred to the visibility of an object situated 5 m from the road verge at a height of 0.5 m. Projective canopy cover over a 5 × 5-m quadrat was estimated to the nearest 10%. The percentage of bare ground on the verge (defined as lack of green vegetation cover) was visually estimated over a 5-m stretch of verge adjacent to the kill. A clinometer and compass were used to determine the aspect and slope at each site five meters into the vegetation. Verge width was measured to the nearest 10 cm from the edge of the road to the edge of unmanaged vegetation. Elevation (m) at road level was recorded using a GPS.

Table 1 – Risk values (m) were determined by subtracting the visibility of each category (taken as 15, 30, 40 and 55 m) from the estimated stopping distance for each recommended speed

Recommended speed (km h^{-1})	<25 m	25–34 m	35–44 m	>44 m
25	6	−9	−19	−34
35	10	−5	−15	−30
45	15	0	−10	−25
50	20	5	−5	−20
55	25	10	0	−15
60	30	15	5	−10
65	36	21	11	−4
75	48	33	23	8
80	54	39	29	14

Risk categories were then assigned as low risk (<0), moderate risk (between 0 and 9), high risk (between 10 and 19) or extreme risk (20 or greater).

In order to evaluate the effect of road curvature on the probability of collisions, a 'risk of collision' index was developed that accommodates the average stopping distances of vehicles travelling at different speeds, including reaction time (source Australian Transport Safety Bureau), and the recommended driver speed at each location (Table 1). Driver visibility was recorded at each location by estimating the distance each driver would have had to see an animal given road curvature, presuming that the animal was on the road from the time of the vehicles earliest appearance (note that this does not account for animals hidden from view that subsequently jump into the paths of vehicles at the last moment). Line of sight was determined by calculating the distance from the kill location to the point of disappearance on the same side of the road based on assessment of the original vehicles approach direction. The 'risk of collision' was calculated by subtracting the visibility distance (m) from the average stopping distance specified for the recommended speed limit at each location (m). Values were designated as low risk (less than 0), moderate risk (between 0 and 9), high risk (between 10 and 19) or extreme risk (20 or greater), as the higher the value, the less chance the driver has of stopping in time. Both driver visibility and the risk of collision index were used in the modelling of fatality probability.

2.3. Traffic speed and volume

The locations of speed limit signs and recommended speed signs (for corners) were marked using a GPS and mapped into the GIS program ArcMap (ESRI, 2002) to show recommended speed zones. Two Trafficorders (TCS Instruments) were used to record hourly traffic volume, vehicle type and individual vehicle speeds on Bundeena Drive and Farnell Avenue. One traffic counter was placed on Farnell Avenue at the point of change from an 80 to a 60 km/h zone (heading east) approximately 200 m from the entrance to the park, while one was placed on Bundeena Drive in an 80 km/h zone roughly 1.5 km from the Bundeena township.

2.4. *Animal movement patterns*

Road usage was assessed by both sand-plots and hair-tubes in an effort to detect as many different species as possible using the roadside verge. Forty-five locations along the road were selected in a random manner, stratified by habitat type. Locations were limited as often there was not sufficient space on the verge for the placement of sand-plots. Locations were also selected on the advice of experts and national parks staff in order to maximize the ability of detecting animals. The size, type and locations of detection devices were specifically chosen to maximize the detection of swamp wallabies, although efforts to accommodate for other species were made. Sand-plots consisted of 2×1 m of sand, 40-mm deep, running parallel to the road. Plots were checked for 19 days in total, between three and seven consecutive days each month (excluding April), depending on weather. Animal prints were noted, along with their size, direction, gait and species, following Triggs (2001).

Once a month, 90 large hair-tubes were deployed for one week to correspond with the checking of the sand-plots. The tubes had a 105-mm entrance diameter and were placed at ground level to maximize detection of swamp wallabies (Lindenmayer et al., 1999; Mills et al., 2002). The bait used was a mixture of peanut butter, honey and oats. Tubes were placed no more than two meters from the road verges at intervals of approximately 250 m (one behind each sand-plot and the remainder between sand-plots). Hair samples were identified by using the computer program Hair ID (Brunner et al., 2002).

2.5. *Fatality hotspots*

A kernel density transformation was applied to fatality presences for each species using Spatial Analyst in ArcGIS. Kernel estimation of point pattern density uses a moving function to weight points within the influence of the function by their proximity to the location where density is being calculated. The area of influence is controlled by the bandwidth of the kernel, with larger bandwidths leading to increased smoothing of the data (Gattrell et al., 1996). For this analysis, a bandwidth of 300 m was used for both mammals and birds as it enabled good resolution of clusters.

2.6. *Predictive modelling*

The use of *k*-fold cross-validation for model selection has been recommended as an appropriate technique for partitioning data into training and testing sets. Cross-validation allows efficient estimation of misclassification error rates by taking average results from several partitions (Fielding and Bell, 1997; Boyce et al., 2002). Tenfold cross-validation was used here (rather than *k*-fold with a different value of *k*) as a compromise between low bias and low variance in error estimation (Hastie et al., 2001). In accordance with this, presences and absences of fatalities were randomly allocated to 10 sets. For each set data were pooled for training with the remaining set used for testing.

Generalized linear models using binomial logistic regression are an appropriate information theoretic approach for biological systems. Generalised linear models were therefore used to examine the ability of a set of predictor variables to explain variation in the presence or absence of fatalities. Rather than modelling each species separately, data were combined into groups of either mammal or bird to provide sufficient data points. Collected fatality information was used in conjunction with absence information from 79 randomly chosen locations along the road. The discrimination ability of the models was assessed by examining the area under a receiver operator characteristic curve (Ferrier et al., 2002). The area under the curve reflects the proportion of both correctly and incorrectly classified predictions over a range of probability thresholds and overcomes the failings of all other threshold dependent measures (Pearce and Ferrier, 2000; Boyce et al., 2002).

Model selection was conducted to find the most parsimonious combination of predictor variables. Selection was done by finding the combination of predictors that possessed the highest area under the curve using the cross-validation process. All other models within one standard error of the best model were included in the best model set (the "one standard error rule", Hastie et al., 2001). To select a single parsimonious model the number of occurrences of each predictor within the 'best' model set, the order of models and the number of variables in each model were compared. Inclusion in the final model was also checked by examining the independent contribution of each predictor to the probability of a fatality across all model subsets using hierarchical partitioning (Mac Nally, 2000; Mac Nally, 2002). Final models were then derived and rerun using the complete data set as recommended by Rencher (1995). All modelling was done using algorithms developed by Ramp et al. (2005) for the R statistical package (R Development Core Team, 2005), although the hierarchical partitioning was run using algorithms developed by Walsh and Mac Nally (2003).

A total of 11 predictor variables were included in the modelling process. Spatial variables were elevation (m), verge width (m), understorey density, canopy cover, bare ground, visibility, risk, and the recommended speed limit. For variables measured on either side of the road, rather than including the values from each side, the mean and difference of each variable was calculated. Models with either the mean or difference were then run separately, with the final model selection process using the mean or difference of each factor that explained the most variation in the response. To include a measure of temporal variation daily values of climate were combined into a drought factor (Australian Capital Territory Emergency Services Bureau, 1998). The drought factor is derived from recent rainfall and the Byram-Keetch Drought index, which is the amount of rain needed to saturate the soil. Also included was the daily traffic volume counted on the day the fatality was recorded.

3. Results

3.1. *Fatalities on roads*

During the five months of this study, 36 mammals were recorded as being killed on the road, the majority of which were swamp wallabies (Table 2). Also killed often were possums and rusa deer. Mammals were killed at a rate of 0.011 per km per day. The most common bird species killed were the honeyeaters (*Anthochaera* sp., *Lichenostomus* sp. and *Phylidonyris novaehollandiae*) and eastern spinebills (*Acanthorhynchus tenuirostris*). Birds were killed at a rate of 0.023 per km per day. Of the mammals killed during the study period, 13 were identified as male, 18 as female and 5 remained unknown. By far the most frequently killed age group were adults, with 27, while there were eight juveniles killed and one unknown. The low numbers of individuals killed prevent more detailed inferences to be made at the species level. For birds, most species were not able to be attributed to a particular sex, although of the birds killed, 68 were adults.

3.2. *Traffic volume and speed*

Farnell Avenue (3096 ± 6.81 vehicles; mean and standard error) was recorded as having nearly 500 more vehicles travelling upon it on a daily basis than Bundeena Drive (2609 ± 1.85 vehicles) when comparing bi-directional daily traffic volume. Traffic leaving the park on Farnell Avenue (west-bound) reached more than two vehicles per minute between 7 and 9 AM and peaked again between 3 and 5 PM (Fig. 1(a)). More than two vehicles per minute on average entered the park along Farnell Avenue between 10 AM and 6 PM (Fig. 1(b)). Traffic volume at night was low, with vehicles travelling in either direction roughly every 10 min (or one every 5 min with both directions combined). Speeds were lower during the day than at night.

Along Bundeena Drive, traffic volume into the town (north-bound) peaked at more than two per minute between 4 and 7 PM, while traffic out of the town (south-bound) peaked between 6 and 10 AM as residents left the township to work for the day (Fig. 1(c) and (d)). After dusk the volume of traffic travelling to Bundeena declined steadily from one vehicle every minute to one every 5–10 min after midnight. The legal speed limit along the monitored stretch of Bunde-

Table 2 – Species recorded as being killed over 22 km of road in the Royal National Park between April and August 2003

Common name	Species name	Total count	% of taxa	% of total kills
Birds				
Little wattlebird	*Anthochaera chrysoptera*	16	21.6	14.3
Yellow-faced honeyeater	*Lichenostomus chrysops*	15	20.3	13.4
New Holland honeyeater	*Phylidonyris novaehollandiae*	11	14.9	9.8
Eastern spinebill	*Acanthorhynchus tenuirostris*	8	10.8	7.1
Red wattlebird	*Anthochaera carunculate*	7	9.5	6.3
Superb fairy-wren	*Malurus cyaneus*	4	5.4	3.6
Beautiful firetail	*Stagonopleura bella*	3	4.1	2.7
Brown thornbill	*Acanthiza pusilla*	2	2.7	1.8
White-eared honeyeater	*Lichenostomus leucotis*	2	2.7	1.8
Silvereye	*Zosterops lateralis*	2	2.7	1.8
Eastern whipbird	*Psophodes olivaceus*	1	1.4	<1
White-browed scrubwren	*Sericornis frontalis*	1	1.4	<1
Painted button-quail	*Turnix varia*	1	1.4	<1
Unidentified		1	1.4	<1
Total birds		74		66.1
Mammals				
Swamp wallaby	*Wallabia bicolor*	14	41.7	13.4
Common brushtail possum	*Trichosurus vulpecula*	6	16.7	5.4
Common ringtail possum	*Pseudocheirus peregrinus*	6	16.7	5.4
Rusa deer	*Cervus timorensis*	4	11.1	3.6
Long-nosed bandicoot	*Perameles nasuta*	1	2.8	<1
Grey-headed flying fox	*Pteropus poliocephalus*	1	2.8	<1
Short-beaked echidna	*Tachyglossus aculeatus*	1	2.8	<1
Total mammals		36		32.1
Reptiles				
Red-bellied black snake	*Pseudechis porphyriacus*	1	50.0	<1
Eastern brown snake	*Pseudonaja textiles*	1	50.05	<1
Total reptiles		2		1.8

Nomenclature follows Strahan (2002) for mammals, Christidis and Boles (1995) for birds, and Cogger (2000) for reptiles.

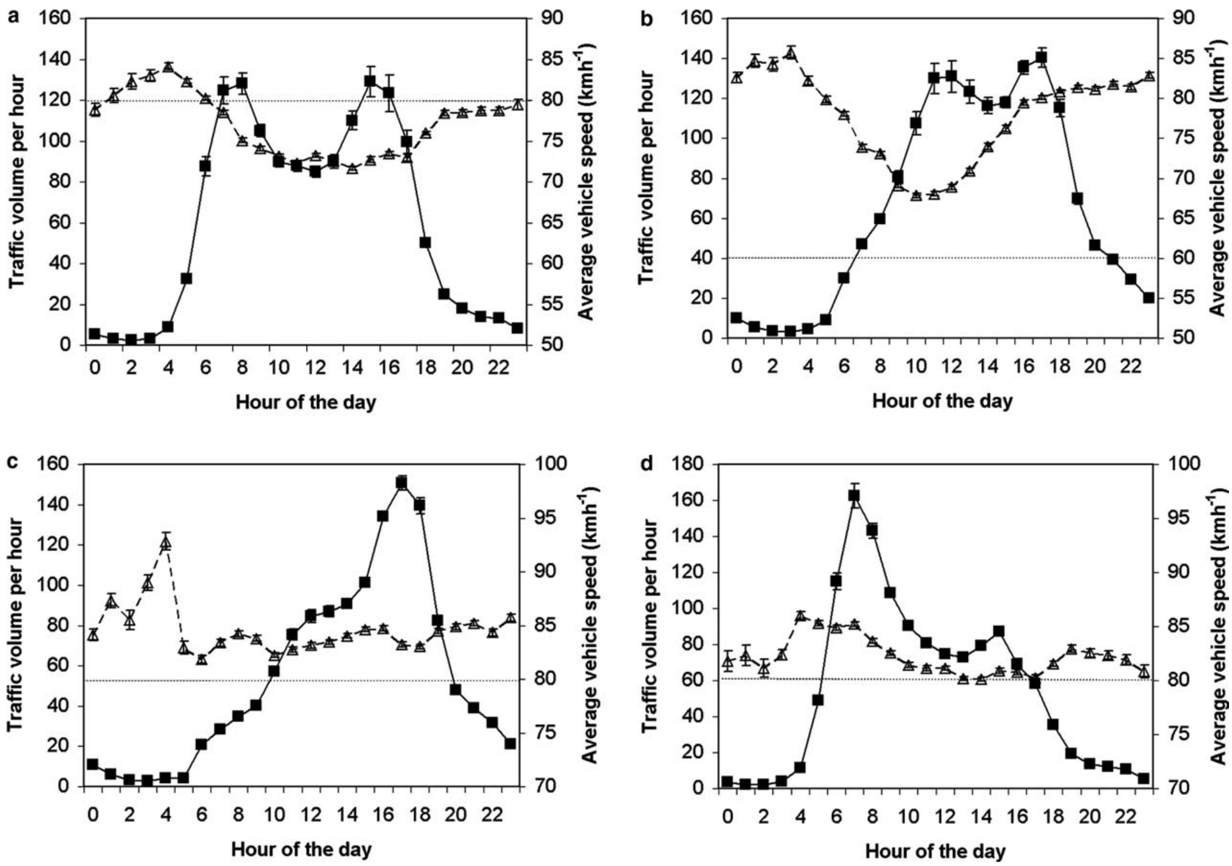

Fig. 1 – Traffic volume (number per hour, squares) and vehicle speed (km/h, triangles) along Farnell Avenue (a) west-bound and (b) east-bound and along Bundeena Drive (c) north-bound and (d) south-bound. Means and standard errors are represented for both, while the legal speed limit is depicted with a hashed line.

ena Drive was 80 km/h, however, at no time was the average speed of vehicles below this speed. In fact, night-time drivers, particularly those coming back to the township in the early morning averaged speeds of up to 95 km/h, with many vehicles recorded as driving in excess of 140 km/h.

3.3. Animal movement around roads

The two techniques employed to detect road usage by animals had strikingly different results. Sand-plots were far better at detecting feral animals (red foxes and rusa deer) than native wildlife (Table 3). Red foxes were the most commonly detected animal using this method, often recorded as moving at speed parallel to the road. The use of hair-tubes had far greater success at detecting the presence of native wildlife, including smaller mammal species. By far the most common species detected were swamp wallabies, with bush rats (*Rattus fuscipes*) and brushtail possums (*Trichosurus vulpecula*) also prevalent.

3.4. Collision hotspots and predictive modelling

Lengths of road with clusters of mammal fatalities (hotspots) occurred at the entrance to the park on Farnell Avenue, near the intersection Sir Bertram Stevens Drive and Bundeena Drive and on the approach to the Bundeena Township (Fig. 2), although fatalities of mammals were noted along most of the road covered in the study. In contrast, fatalities of birds were most common on Bundeena Drive, with a hotspot 3-km north of the Sir Bertram Stevens Drive and Bundeena Drive intersection and another hotspot on the approach to the Bundeena Township (Fig. 2).

For modelling purposes all fatalities of mammals were combined into one category rather than analysing each species separately as numbers were sparse. Of the 2048 model combinations only two were selected in the best model set as no other models had areas under the curve within one standard error. The best model included five of the 11 predictor variables used (Table 4) and explained 20% of the variation in the probability of a fatality occurring during the study period. The area under the curve provided only moderate confidence in the reliability of the model. The temporal variable drought factor was positively correlated with fatality probability, as was collision risk. The verge width, understorey density and the percentage of bare ground were all negatively associated with fatality probability. Of the five predictors, the mean percentage of bare ground on either side of the road was by far the most important independent contributor, accounting for 23% of the total variance explained (Table 5).

As for mammals, all bird species found were combined into one group for modelling purposes. There were four models within one standard error of the model with the highest

Table 3 – Animal presence along the road in the Royal National Park, recorded as either tracks of animals in sand-plots, identifying their direction and gait, or as counts of animal hairs in hair-tubes

Species	Direction	Gait	Tracks	Hairs
Red fox (*Vulpes vulpes*)	Towards	Walk	7	2
	Away	Walk	2	
		Trot	6	
	Parallel	Walk	1	
		Trot	1	
		Gallop	3	
	Unknown	Unknown	1	
Rusa deer (*Cervus timorensis*)	Away	Walk	2	
		Unknown	2	
	Parallel	Unknown	1	
Swamp wallaby (*Wallabia bicolor*)	Away	Hop	3	31
Cat (*Felis catus*)	Towards	Walk	1	
Brushtail possum (*Trichosurus vulpecula*)	Parallel	Walk	1	7
Australian Raven (*Corvus coronoides*)	Towards	Walk	1	
	Parallel	Walk	1	
Unknown possum				2
Brown antechinus (*Antechinus stuartii*)				1
Unknown antechinus (*Antechinus sp.*)				1
Bush rat (*Rattus fuscipes*)				9
Swamp rat (*Rattus lutreolus*)				1
Unknown mammal				5

area under the curve. While the recommended speed limit, mean slope and verge width were present within this best model set, the final model was chosen to include the percentage of bare ground, understorey density and canopy height as they were present in each of the models in the best model set (Table 4). This model accounted for 34% of the variation in

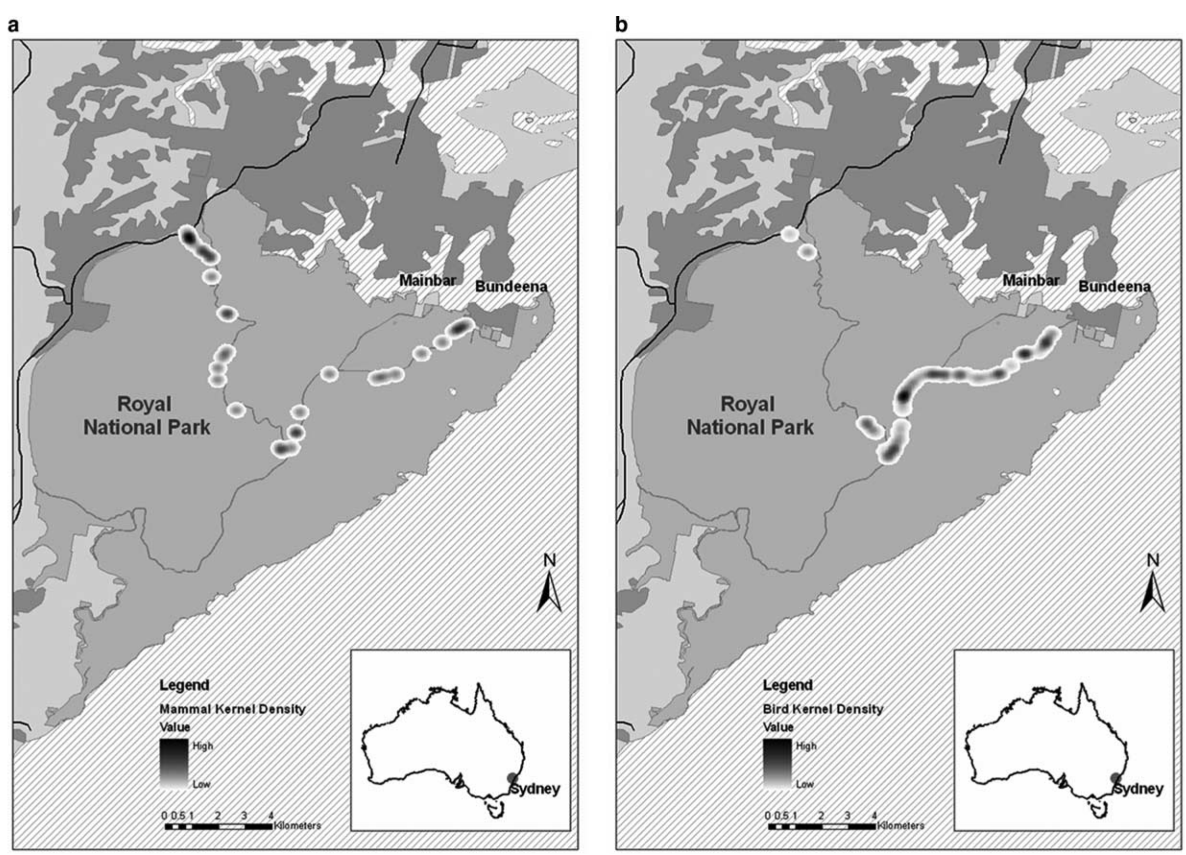

Fig. 2 – Kernel density of (a) mammal fatalities and (b) bird fatalities in the Royal National Park. The darker patches of density estimates reflect locations that can be considered 'hotspots'. Dark grey areas represent urban areas, medium grey represent the area belonging to the park, while light grey areas are unbuilt regions. Slanted lines indicate the presence of water bodies and the Pacific Ocean.

Table 4 – Final models identified by the model selection procedure

Species	Predictors	Deviance		% Deviance	
		Null	Residual	Explained	AUC
Mammals	DF + VD + UM + BM + RISKM	142.9 (114)	114.9 (109)	19.7	0.755 (0.007)
Birds	BM + UD + HM	211.9 (152)	140.3 (149)	33.8	0.828 (0.002)

The deviance explained by each of the using the complete data set with degrees of freedom in brackets along with the area under the receiver operator characteristic curve (AUC ± SE) is presented. The predictors are drought factor (DF), verge width difference (VD), mean understorey density (UM), understorey density difference (UD), mean percentage bare ground (BM), mean risk (RISKM), and mean canopy height (HM).

Table 5 – Variable coefficients, standard errors and Z-scores for the best model selected

Species	Variable	Coefficient	SE	Z	P	Independent contribution
Mammals	Constant	3.355	1.770	1.895	0.058	
	DF	0.136	0.097	1.406	0.159	9.06
	VD	−0.004	0.003	−1.394	0.163	7.31
	UM	−2.312	0.971	−2.383	0.017	10.09
	BM	−3.588	1.132	−3.170	0.002	22.57
	RISKM	0.712	0.452	1.576	0.115	8.58
Birds	Constant	6.352	1.182	5.375	<0.001	
	BM	−5.766	1.292	−4.463	<0.001	24.08
	UD	2.147	0.858	2.502	0.012	10.9
	HM	−0.774	0.175	−4.410	<0.001	29.17

The independent contribution of each variable as determined by hierarchical partitioning is presented as a percentage of the total explained variance. The predictors are drought factor (DF), verge width difference (VD), mean understorey density (UM), understorey density difference (UD), mean percentage bare ground (BM), mean risk (RISKM), and mean canopy height (HM).

fatality probability and the area under the curve provided reasonable confidence in the model. Of the final predictors chosen, canopy height and the percentage of bare ground were the most important contributors to the total variance explained (Table 5). As for mammals, the percentage of bare ground was negatively correlated with the probability of a fatality occurring, while canopy height was also expressed as a negative relationship.

4. Discussion

By conducting surveys along the most frequented route within the park, it was established that a range of both native and exotic fauna are being lost through collisions with vehicles. Estimates were restricted to a five month, yet intensive, sampling period, and so present only a snapshot of this issue. Data collected over a longer period would be necessary to quantify long-term variation in collisions that may result from changes in animal behaviour with seasonal conditions and breeding patterns or from long-term environmental patterns such as drought. The survey was also restricted to being conducted from a vehicle in order to cover the road length on a daily basis, and this would certainly lead to an underestimate of fatalities, especially for amphibians and reptiles (Slater, 2002). Although some reptile fatalities were recorded, analyses were restricted to birds and mammals. In addition, given the number of fatalities observed, strong conclusions about sex and age bias in fatalities of different species were unable to be made. Future surveying will address this issue.

Traffic volume and speed are generally regarded as being important factors explaining road fatalities (Forman and Alexander, 1998; Hubbard et al., 2000; Jones, 2000; Trombulak and Frissell, 2000; Dique et al., 2003; Seiler, 2003), and hence much of Australia's previous research has focused on major roads and highways. However, the road avoidance effect (Forman and Alexander, 1998), resulting from the 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). It follows that high fatality rates are more likely to occur on roads with high speed limits and moderate to low traffic volumes adjacent to habitat containing abundant wildlife. Indeed, fatality rates of macropodids along the Silver City Highway, north of Broken Hill, New South Wales, which has an average of only 60 vehicles per day were around 0.035 per km per day pre-drought (Lee et al., 2004). This rate is markedly similar to fatality rates recorded on other roads with much higher traffic volumes (Taylor and Goldingay, 2004; Ramp et al., 2005), discounting variation in population densities. The behaviour of animals in different circumstances is often overlooked when modelling fatalities on roads in relation to traffic flow (van Langevelde and Jaarsma, 2004), although models taking animal speed into account have suggested that slow moving species are at greater risk (Hels and Buchwald, 2001). It is likely that the combination of low to moderate traffic volume and the high speeds observed within the Royal National Park is contributing to the frequency of collisions.

Efforts to quantify road usage by fauna within the park returned strikingly different results depending upon the technique employed. The use of sand-traps placed on the roadside verge was particularly successful at detecting exotic fauna, namely red foxes and rusa deer. By monitoring the direction and gait of movement it was determined that foxes were using the roadway as a means for travelling between regions of the park. The use of roads and fire trails has been noted as a frequent mechanism facilitating the movement of feral predators (May and Norton, 1996), and is another way that roads impact on wildlife. Despite the frequency of movement no fatalities of red foxes were observed during the study period, inferring that they may be adept at avoiding collisions. In contrast to the sand-traps, hair-tubes were successful in enabling the detection of native species along roadsides. They indicated that swamp wallabies were frequent users of the roadside verge, along with bush rats and brushtail possums, and these were the most frequently killed mammal species. The absence of bush rats may indicate that this species is able to avoid collisions (Hels and Buchwald, 2001), or that fatalities were not detected by our sampling methodology (Slater, 2002). On their own these data do not provide an indication of road avoidance or attraction as no samples were taken away from the road, however, they do show that these species are susceptible to fatalities as they are utilising roadside habitat and identifies them as potential targets for future research.

4.1. *Fatality hotspots and models*

For mammals, collision hotspots were identified at the entrance to the park, near the intersection of Sir Bertram Stevens Drive and Bundeena Drive and on the approach to the Bundeena Township. Any cost-effective approach to the management of road-based fatalities within the park should focus on these hotspots. Given that monitoring of traffic volume and speed suggested that the legal speed limits were not adhered to, particularly at night when most animals are using the road environment, it seems that a simple reduction of the speed limit in these locations may not solve the problem, although a lower vehicle speed would provide better opportunities for both animals and vehicles to avoid collisions (van Langevelde and Jaarsma, 2004). Other mitigation efforts will be necessary to guarantee a reduction in vehicle speed at night, such as traffic obstacles and speed bumps (Jones, 2000). Long-term collection of fatality information is recommended to provide a more rigorous understanding of hotspot locations, combined with surveys of population density to clarify the relationship between density and fatality probability.

The percentage of bare ground and understorey density contributed most to mammal fatality probability, when fatalities of all mammal species were clumped. While this biases information towards common species, fatality information would need to be collected over a much larger temporal period to model fatalities of less common species. The percentage of bare ground is actually the inverse of the amount of forage on the verge. Therefore, the model suggests that as the amount of forage on the verge increases, so did the likelihood of a fatality. These results corroborate anecdotal evidence that suggest that many wildlife species are attracted to roads to gain access to the typically high quality forage abundant on the road verge, although some mammal species are known to avoid it (e.g., hedgehogs, Rondinini and Doncaster, 2002). Understorey density is analogous to the amount of shelter and protection offered to wildlife on the roadside, particularly for small to medium sized mammals (Clevenger et al., 2003). In contrast to the findings for snowshoe hares (*Lepus americanus*) and other mammals (Bellis and Graves, 1971; Clevenger et al., 2003), where fatalities increased in proximity to vegetative cover, mammal fatalities in this study were found to decrease as the amount of shelter (or understorey density) increased. It is possible that the safety and security that this understorey provides lessens the likelihood that animals will take aversive action when a vehicle approaches, although it has also been suggested that a lack of cover can inhibit movement across roads (Bennett et al., 1994; Goosem, 2001), thereby reducing the chance of a fatality. The behavioural ecology of a species is likely to have a large impact on fatality probability, and more information on how Australian fauna, and fauna from other countries, behave around roads is necessary to further quantify this issue.

Roads are known to affect bird density, diversity and behaviour (Reijnen et al., 1996; Forman et al., 2002; Gutzwiller and Barrow, 2003; St Clair, 2003). It is therefore not surprising to see that small-scale features of roadside habitat influence the probability of fatalities, leading to roadside habitat acting as a sink for some bird species (Mumme et al., 2000). In this study, the likelihood of a fatality decreased as canopy height increased, suggesting that tall trees force birds to fly higher off the ground, and therefore avoid vehicles, or that the suite of species killed tend to utilise lower canopied habitat such as heath. Certainly much of Bundeena Drive, where the majority of bird fatalities were recorded, is dominated by Sandstone Heath vegetation, but the most commonly killed species (little wattlebird, yellow-faced honeyeater and new-Holland honeyeater) would not be restricted to the heath habitat as they also favour woodland and forest habitat. This finding confirms reports from other studies, where tall roadside vegetation reduced collision frequency (Bekker et al., 1995; Clevenger et al., 2003). That bare ground is also negatively correlated with fatalities suggests that this factor may be a correlate for some other attribute, as the types of birds killed were not ground feeders.

These findings provide insights into how fine-scale patterns of roadside vegetation influence the likelihood of a fatality. Most fatality modelling has tended to use variables at much larger scales, with variables typically derived from GIS data layers (Clevenger et al., 2003; Malo et al., 2004; Ramp et al., 2005; Seiler, 2005). The benefits of fine-scale modelling are the insights into specific aspects of road design and characteristics of the immediate road environment that may lead to the development of informed mitigation strategies. Both mammal and bird models did not explain all of the variation in fatalities, suggesting that there may be unaccounted for causes of fatalities. The risk of collision index was retained in the final model for mammals, suggesting that as the risk increased so did the likelihood of a collision. The success of this index warrants further investigation in other systems, and highlights that factors that reflect the risk of collision should be included in predictive models of fatalities, not just factors that reflect the presence of animals or vehicles (Seiler, 2003).

4.2. *Conservation implications*

The management of road impacts is an important consideration for isolated reserves, particularly those situated in the urban fringe (Ramp and Ben-Ami, in press). For wildlife, the key issue is how impacts are felt across the landscape. Roads are unlike most other causes of fragmentation in that they continue to remove individuals through collisions with vehicles. There is speculation that roads may form habitat 'sinks' for wildlife (Bennett, 1991; Forman and Alexander, 1998), drawing animals from surrounding areas, ultimately to their doom. There is almost no knowledge of these population processes yet they are crucial to evaluating the long-term viability of wildlife populations in this landscape. Using the data collected in this study, research has recently been conducted to examine the impact of road-based fatalities on the survival of the swamp wallaby population within the Royal National Park (Ramp and Ben-Ami, in press). Using a population modelling approach, this research has suggested that the population is currently in decline. Importantly, the modelling predicted that this decline could be reversed by a reduction of female wallaby fatalities on roads of 20%, providing conservation managers with a specific mitigation target.

The impact of roads can be measured in terms of the survival of species in road environments, such as in studies of bobcats (*Lynx rufus*) in southern Texas (Cain et al., 2003) and the Florida Key Deer (*Odocoileus virginianus clavium*) in southern Florida (Lopez et al., 2004). Despite the importance of this issue for conservation there is still very little knowledge available of how most wildlife species survive in and use road-affected environments. For example, Jaeger et al. (2005) recently developed an interactive model of the relationship between roads and population risk yet they acknowledge that little quantitative data on the effect of roads on populations exists. Protected reserves in peri-urban environments like the Royal National Park represent a test of our ability to balance the needs of wildlife with those of our own.

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