Available online at www.sciencedirect.com
SCIENCE DIRECT®

Biological Conservation 126 (2005) 474–490

BIOLOGICAL CONSERVATION

www.elsevier.com/locate/biocon

Modelling of wildlife fatality hotspots along the Snowy Mountain Highway in New South Wales, Australia

Daniel Ramp [a,*], Joanne Caldwell [b], Kathryn A. Edwards [a], David Warton [c], David B. Croft [a]

[a] School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, NSW 2052, Australia
[b] New South Wales Department of Environment and Conservation, Tumut, 2720, New South Wales, Australia
[c] Department of Statistics, School of Mathematics, University of New South Wales, Sydney 2052, Australia

Received 9 February 2005
Available online 19 August 2005

Abstract

The effects of roads on the natural environment is of growing concern world-wide and foremost amongst these effects are the fatalities of wildlife killed in collisions with vehicles. Aside from animal welfare and human safety considerations, fatalities may have significant impacts on the population dynamics of species living adjacent to roads and thus can adversely affect the viability of local populations. As such, the need to quantify and mitigate road-based fatalities is paramount. With a vast expanse of roads it is imperative to identify where animals are most likely to be killed (i.e. hotspots) and what are the contributing factors. In order to identify hotspots, we develop a modelling approach for both presence and presence/absence data. We use data collected from the Snowy Mountain Highway in southern New South Wales, Australia, to compare the effectiveness of this approach for five species/groups of species. We observed that models of species killed in a clumped fashion were effective at identifying hotspots, while for species where fatalities were distributed evenly along the road the models were less effective. We recommend that where actual presence data exists spatial clustering is the preferred method of hotspot identification. Predictive models of presence/absence date should be constructed if the intention is to extrapolate to additional areas. The added benefit of predictive models are that they enable the identification of explanatory factors and this knowledge enables species-specific management strategies to be developed and implemented at hotspot locations.

Keywords: Road-based fatalities; Hotspots; Predictive models; Kernel density estimates; Wildlife populations

1. Introduction

The effect of roads and traffic on habitat and wildlife is far-reaching. Community perception of this issue is not new, but consideration of roads as driving forces in ecology has only recently gained international awareness (Sherwood et al., 2002; Forman et al., 2003). Recent studies show that roads have a multitude of effects on the natural environment such as impacts on microclimate (Ellenberg et al., 1981; cited in Forman et al., 2003), wind flow (Ahrens, 1991), run-off and water flow (Federal Highway Administration, 1996), addition of noise pollution (Reijnen et al., 1997) and facilitation of the dispersal of both plants and animals (Tikka et al., 2001), including weeds (Ullmann, 1998), feral animals (Seabrook and Dettmann, 1996; Stiles and Jones, 1998) and native species (van der Ree, 2002; Spooner et al., 2004). For wildlife, roads have numerous impacts on populations (Forman and Alexander, 1998). Roads can form barriers to movement, fragmenting populations and

* Corresponding author. Tel.: +61 29 385 2111; fax: +61 29 385 1558.
E-mail address: d.ramp@unsw.edu.au (D. Ramp).

0006-3207/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.biocon.2005.07.001

isolating them from resources and mates (Richardson et al., 1997; Gerlach and Musolf, 2000; Dyer et al., 2002). They can alter the structure of populations adjacent to roads where road effects lead to avoidance (Forman et al., 2002). Perhaps most obviously roads cause fatalities of animals as a result of collisions with the vehicles that travel on them (Malo et al., 2004; Saeki and Macdonald, 2004). These impacts raise serious concerns about the stability and sustainability of roadside wildlife populations, as well as raising welfare issues of the animals and humans injured and killed from collisions.

Conflict between humans and wildlife at the road interface will likely increase with the expansion of urban areas world-wide. It has been well documented that fatalities of native wildlife in Australia are of great concern, as carcasses of kangaroos, wallabies, wombats and possums litter the road environment (Andrews, 1990; Bennett, 1991). Studies of wildlife fatalities on roads in Australia have, so far, focused largely on Macropodids (Coulson, 1982; Osawa, 1989; Brown, 2001; Klöcker, 2003; Lee et al., 2004), with some attention to other conspicuous fauna such as koalas (*Phascolarctos cinereus*) (Dique et al., 2003), common wombats (*Vombatus ursinus*) (Brown, 2001), Tasmanian Devils (*Sarcophilus harrisii*) and eastern quolls (*Dasyurus viverrinus*) (Jones, 2000), and eastern barred bandicoots (*Perameles gunnii*) (Driessen et al., 1996; Mallick et al., 1998), although a few more comprehensive studies have also been done (Vestjens, 1973; Cooper, 1998; Taylor and Goldingay, 2004). Apart from documenting fatalities, specific attention has been paid to roads as a barrier to small animal movements (Goosem, 2001, 2002), fatalities as an index of abundance (Mallick et al., 1998) and habitat use (Driessen et al., 1996), male sex bias in fatalities (Coulson, 1997), the effect of drought on fatalities (Coulson, 1989; Lee et al., 2004), the efficacy of various mitigation measures (Jones, 2000; Bender, 2001; Abson and Lawrence, 2003; Dique et al., 2003) and the influences of environmental (road and habitat) and temporal variables on the frequency of animal collisions (Brown, 2001; Klöcker, 2003; Taylor and Goldingay, 2004).

Given the extent of wildlife killed on roads there is a pressing need to alleviate both fatalities and secondary impacts on wildlife populations. With 810,022 km of sealed and unsealed roads in Australia as of 2002 (Australian Bureau of Statistics), it is both prohibitively costly and logistically impossible to manage these impacts along every segment of road. A framework is therefore needed to focus mitigation efforts in order to maximise effort, and the best approach to do this is by identifying and targeting fatality hotspots (sometimes called blackspots). Given the complexity of the many factors contributing to fatalities it is necessary to model the locations of collisions between vehicles and wildlife. The aims of this modelling process are two-fold; firstly to develop predictive models to enable identification of hotspots in different locations and times, and second to identify explanatory variables influencing the probability of collisions and the resultant wildlife fatalities (Mac Nally, 2000). The primary motivation for most research examining wildlife fatalities has been for the latter (Puglisi et al., 1974; Bashore et al., 1985; Joyce and Mahoney, 2001; Clevenger et al., 2003), although researchers have also used data on wildlife fatalities to produce estimates of population indices (Mallick et al., 1998; Baker et al., 2004; Saeki and Macdonald, 2004). Only a few recent studies have specifically focused on the development of predictive models of fatalities (Finder et al., 1999; Nielsen et al., 2003; Malo et al., 2004; Saeki and Macdonald, 2004; Seiler, 2004). Predictive models are useful in that they can be extrapolated to other areas and times, although care must be taken to ensure the validity of the models to do this. They can therefore be used to identify areas to be targeted for mitigation, provide information on new road design and predict what impacts roads might be having on local wildlife populations. More importantly they can be also be used to identify those factors contributing to the likelihood of fatalities.

Here we provide a framework for recording fatality information, developing predictive models and identifying hotspot locations. To do this we used data collected along the Snowy Mountain Highway between the townships of Tumut and Talbingo in southern New South Wales, Australia. Two and a half years of data collected using a customised GPS logger is compared to four years of previously recorded fatality information for the same length of road. Using the GPS collected data we implement two approaches to modelling hotspot locations. The first is an assessment of the spatial clustering of presence only data using kernel density estimation and a network *K*-function. The second is a modelling approach that enables the identification of both hotspot locations and those factors contributing most to fatality occurrence. Both approaches are applied to five species or groups of species covering the most abundant wildlife species in the region. The usefulness of establishing a common approach to hotspot identification and the subsequent targeting of hotspots by various management strategies is discussed.

2. Methods

2.1. Study area

The road surveyed in this study was a 40-km segment of the Snowy Mountain Highway, running between the townships of Tumut (35°19′S, 148°14′E) and Talbingo (35°34′S, 148°18′E) in southern New South Wales, Australia. The western side of the road is dominated by the Blowering Reservoir which sits at the base of the Snubba Range (Fig. 1). Along the eastern side of the road lie the mountainous regions of Kosciusko National Park, including Mount Bogong at

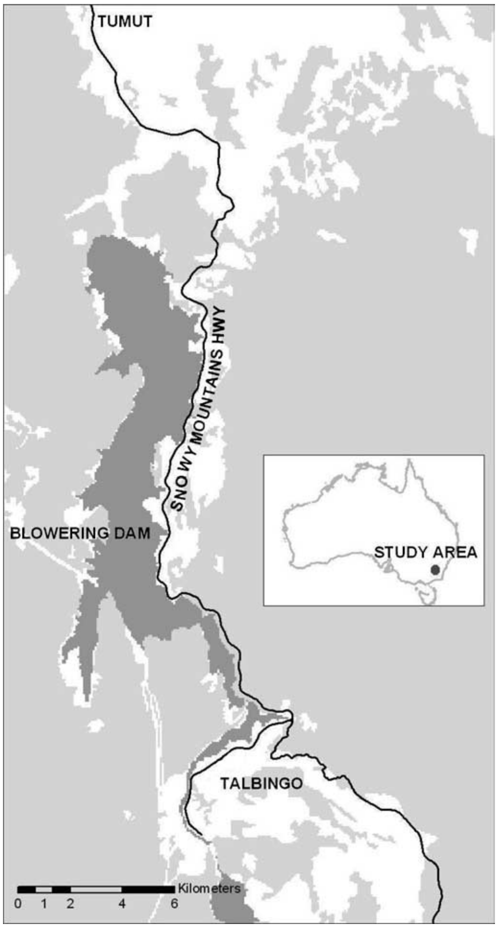

Fig. 1. Map of the study location, showing the Snowy Mountain Highway between the townships of Tumut and Talbingo, south-western New South Wales, Australia. Vegetated areas are indicated by light grey, while cleared areas are white.

1092 m. The vegetation surrounding the road is dominated by cleared land, moist forest and dry forest. The climate is temperate, with a mean annual rainfall of 907 mm and winter rainfall twice that during the summer (Australian Bureau of Meteorology records for Tumut Plains).

The section of the Snowy Mountain Highway studied has a speed limit of 100 km h^{-1}. Representative traffic volume estimates for this segment of road were obtained from the New South Wales Roads and Traffic Authority for February 2000 and August 2003. Traffic monitoring over 14 days in February 2000 saw an average of 263 vehicles per day travel south and 273 per day travel north. In August 2003 traffic monitoring recorded an average of 222 vehicles per day travel south and 231 per day travel north. For the data collected we were able to calculate the average total traffic volume (summed for both northbound and southbound traffic and summed across both the sampling years of 2000 and 2003) and their 95% confidence intervals (Fig. 2).

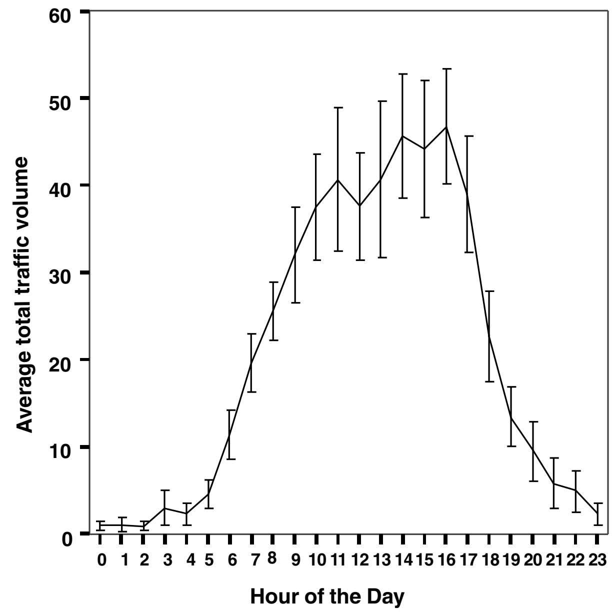

Fig. 2. Average traffic volume counts of the total number of vehicles travelling along the Snowy Mountain Highway in both a north and south direction, summed across the years 2000 and 2003. Values presented are means for each hour and their 95% confidence interval.

2.2. Data collection

2.2.1. Fatality surveys

Counts of wildlife killed along the Snowy Mountain Highway were recorded between 1998 and 2002. One of us (JC) travelled the road recording the species of animal killed from a vehicle travelling at 60 km h^{-1} on a mostly daily basis, typically twice per day five days per week. Carcases were removed from the roadside after recording to avoid double counting. Animals found by other members of the local New South Wales Wildlife Information and Rescue Service chapter were included in the analysis where it was certain such kills were not previously recorded. Data were collected in this way until March 2002 when an improved system of monitoring was implemented. A list of species recorded is included as Appendix 1.

We developed a simple hand-held device for recording fatalities to minimize driver distraction and facilitate registering locations via a GPS. A custom five-button hand-sized box was designed by GPS Data Loggers (R.I. Keskull, Australia) and attached to a Garmin II Plus GPS unit mounted to the dash-board of a vehicle. Each of the five buttons was assigned to a particular species or group of species for recording of fatalities. For this study along the Snowy Mountain Highway the categories recorded were eastern grey kangaroos (*Macropus giganteus*), swamp wallabies (*Wallabia bicolor*) and red-necked wallabies (*Macropus rufogriseus*) combined, common wombats (*V. ursinus*), feral animals including European rabbits (*Oryctolagus cuniculus*), red foxes

(*Vulpes vulpes*) and cats (*Felix catus*), and birds. The date, time and GPS location of each carcass was recorded. In addition, fixes were taken every 10 s to determine the route travelled by the vehicle, providing information on those segments of road where carcasses were absent. The previous pattern of recording was continued between March 2002 and June 2004 with the use of data logger.

2.2.2. Data acquisition and variable determination

A digital data set containing the location of presence and absence data points for each species was compiled from the GPS survey data and entered into a Geographic Information System (GIS) using ESRI ArcGIS. Absence data points were randomly selected, using the Hawth's Analysis Tools add-on for ArcGIS (Beyer, 2004) to make the total number of data points 2136 (double the number of the most frequent killed species). Absence points were randomly selected along the road to eliminate any potential bias.

Variables were only considered for inclusion in models if: (a) they were known from previous work to be related to fatalities; (b) they were factors not specific to this road (so the model can be used for other roads); (c) they were factors for which biologically important variation occurs over a scale that can be targeted in management; and (d) the factors were not closely related to each other (to minimise colinearity). Considerations (a) and (d) follow standard recommendations for variable selection, while (b) and (c) are important considerations in developing a model that can be used by managers to identify high risk road sections and minimise such risks. Where a number of closely related variables were available for each predictor, binomial logistic regressions were performed for each variable separately, with the most explanatory variable selected for inclusion in the full model set.

For each data point, attributes describing both spatial and temporal differences were derived. Data sets used in this process were a 25-m Digital Elevation Model, a vegetation cover data set derived from 30-m LANDSAT data and a digital road network. These were supplied by the New South Wales Department of Environment and Conservation and the New South Wales Department of Lands. Data sets of rainfall (mm) and the Southern Oscillation Index were obtained from the National Climate Centre at the Australian Bureau of Meteorology. Values of these temporal variables were calculated over periods of one, three or six months. For each species, only the period that explained more of the variation in fatalities was used in the modelling process.

In order to derive landscape attributes (or spatial variables) for fatality locations, researchers have typically created buffer zones around each location point. For example, Finder et al. (1999) and Hubbard et al. (2000) both used buffers of 0.8 km either side of the road, while Nielsen et al. (2003) used a buffer of 0.1 km. Malo et al. (2004) opted for a circular buffer zone with a radius of 1 km. The choice of buffer size may profoundly affect the values of predictor variables scored for this region (e.g. proportion of forested area), hence there is good reason to base buffer distances on the ecology and behaviour of the particular species in question and the scale of prediction being undertaken. We did not choose an arbitrary buffer size but chose one based on the species/group behaviour and ecology, namely an estimate of the average home range size.

The digital vegetation cover data set for the area surrounding the Snowy Mountain Highway is comprised of five dominant forest communities (moist forest, moist forest tending to dry, disturbed moist forest, severely disturbed forest and dry forest) plus cleared land. To examine how habitat influenced the likelihood of collisions, the area covered by all forest communities, as opposed to cleared land, was aggregated and expressed as a proportion of the area covered by forest. To determine the buffer size for this calculation, a circular sampling area based on the size of each species home range was derived using sizes described from other studies, with the exception of birds (Johnson, 1987; Troy and Coulson, 1993; Moore et al., 2002; White et al., 2003; Skerratt et al., 2004). As the point on the road might be at the edge of an animal's home range, the diameter of each species' home range was used as the radius of a circle from each point along the road, where the radius of the circle was equal to the diameter of the average reported home range of each species (714 m for *M. giganteus*, 704 m for wallabies, 320 m for *V. ursinus*, and 196 m for feral animals [based upon *O. cuniculus*]). As home range sizes vary between different studies and locations, values were chosen to reflect probable sizes as a working model. Data on actual sizes at the location are currently being collected at the field site. For birds, the distance from each location point to the nearest forest was used because a logical home range could not be approximated. Proportions of forest were arcsine transformed prior to analysis.

The attributes of slope (degrees), elevation (m) and aspect (degrees) were derived from the Digital Elevation Model for the area surrounding each data point. Values for aspect were transformed to an index to overcome circularity and then reorientated along the south-east/north-west axis where $1 = 135°$ (SE, cooler) and $0 = 315°$ (NW, warmer) using a modified version of the northern hemisphere index described by Beers et al. (1966). The distance from each data point, as defined by the Digital Elevation Model, to water (m), to the nearest town (m) and to the nearest gully (m) were recorded. To account for the effect of road curvature on driver visibility and subsequent likelihood of a collision, an index of sinuosity for each data point was derived by calculating the Euclidean distance between two points on the road either side of each location. Sinuosity values were calculated over 100, 250 and 500 m. Higher values of this index indicate greater curvature of the road. For each species only the distance that explained more of the variation in fatalities was used in the modelling process.

2.3. Statistical analysis

2.3.1. Spatial clustering of fatalities

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 500 m was used for each species to make estimates comparable. This bandwidth was chosen as an appropriate scale as it lends itself well to any potential mitigation efforts.

To further investigate the degree to which clustering occurs within each data set, a network K-function was used (Okabe and Yamada, 2001). The network K-function is an adaptation of Ripley's K-function which describes the dispersion of data over a range of spatial scales (Ripley, 1976). This is done by calculating the average number of points within a distance d from each point in the data set, and then dividing this amount by the overall study area to give $\mathrm{K}(d)$, repeated for increasing values of d (O'Sullivan and Unwin, 2003). Instead of calculating the K-function using a 2-dimensional surface, the network K-function modifies the statistic to work with distances along a network (Okabe and Yamada, 2001). A similar modification of the K-function has been used by (Clevenger et al., 2003) to assess spatial clustering of road fatalities of mammals and birds along two roads in Alberta, Canada.

The SANET version 2.0 extension for ArcGIS (Okabe et al., 2003) was used to calculate the observed network K-function for records of roadkill for each of the five types of species, with d increasing by increments of 500 m. The expected values for the network K-function at each of these increments of d were approximated with 100 Monte Carlo simulations. Results were modified to show the incremental value of K for each additional 500 m rather than the cumulative value and totals were standardised to allow for comparison between each species. The difference between the observed K-function values and the values that would be expected if the points were randomly distributed along the network is referred to as the L statistic (O'Sullivan and Unwin, 2003). Positive values of L indicate that clustering of the data points are occurring at that scale, whereas negative values imply dispersion of the data.

2.3.2. Predictive modelling

2.3.2.1. Model selection. The use of k-fold cross-validation 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). Five-fold 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). As such, the road between Tumut and Talbingo was divided into five continuous equal-length segments so that presences and absences of fatalities could be allocated to five validation sets. For each combination of four sets, data were pooled for training with the remaining set used for testing so that a different, albeit adjacent, segment of road was used for validation.

Generalized linear models using binomial logistic regression were estimated for each possible model subset using the chosen predictor variables, with the dependent variable as the presence or absence of fatalities. This process was repeated for each species or group of species using the cross-validation process. The discrimination ability of the models was assessed by examining the area under a receiver operating 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 (Pearce and Ferrier, 2000; Boyce et al., 2002). The bigger the area under the curve, the better the predictive ability of the model (Manel et al., 2001). Receiver operating characteristic curves have been recommended to be used to estimate the predictive ability of binomial models, particularly for species detection and habitat selection models (Pearce and Ferrier, 2000; Manel et al., 2001; Gibson et al., 2004a). Models of fatality detection differ only in that the spatial distribution of detection follows linear trajectories rather than across landscape grids.

The combination of predictors with the highest area under the curve was found and we used the one standard error rule (derived from the area under the curve for each cross-validation set) to select the 'best' models (Hastie et al., 2001). To select a single parsimonious model for each species we compared the number of occurrences of each predictor within the 'best' model set, the order of models and the number of variables in each model. On these recommendations, final models were derived and rerun using the complete data set as recommended by Rencher (1995). All modelling was done using algorithms we developed for the R statistical package (R Development Core Team, 2005).

Evaluating the influence of predictor variables on a dependent variable in multiple regression is problematic and confounded by multicollinearity, hence we used the method of hierarchical partitioning as recommended by Mac Nally (2000, 2002) and recently implemented in numerous studies (Gibson et al., 2004b,c). Hierarchical partitioning examines all model combinations jointly to identify average influences of predictive variables rather than just from the single best model. The goodness-of-fit measure log-likelihood was used to underlie the partitioning of variation in order to estimate the percentage independent contribution of each predictor variable to the total explained variation in the dependent variable (fatalities). Hierarchical partitioning was run using the complete data set and conducted using algorithms developed for the R statistical package (Walsh and Mac Nally, 2003).

2.3.2.2. Model implementation. In order to obtain probability distributions for the final models, and hence identify hotspot locations, a point was assigned every ten metres along the road network. Coefficients derived from each model were then used to calculate the probability of a fatality occurring at each point over the study period. For temporal variables, average values were used ($R1 = 62$ mm, $R3 = 180$ mm, $R6 = 374$ mm, $SOI_1 = -5$, $SOI_3 = -4.6$, $SOI_6 = -4.5$). To identify hotspot clusters the 95th percentile of probability values were labelled, with the exception of wallabies and common wombats where the 90th percentile of probability values were used. The different percentiles were chosen to provide good delineation between hotspot size and the spread of data of each species.

3. Results

3.1. Traffic volume

From the data we could obtain we observed that during our survey period most traffic traversed the Snowy Mountain Highway during the day (Fig. 2). However, the majority of species killed were crepuscular or nocturnal and presumably did not frequent the road often during the day. It is therefore likely that the majority of fatalities are being caused by only very few vehicles. While high traffic volume is often thought of as being correlated with high fatality frequency (van Langevelde and Jaarsma, 2004), roads like the Snowy Mountain Highway that are travelled infrequently but at speed often incur high fatality rates as species do not appear to become habituated to vehicle presence.

3.2. Wildlife fatalities along the Snowy Mountain Highway

From 1998 to the end of 2003 there were 2529 eastern grey kangaroos, 221 wallabies, 166 wombats, 952 feral animals and 596 birds recorded as being killed along the highway (Table 1). These values are likely to underestimate fatalities as partially wounded animals that escape and die away from the road would not be recorded, plus fatalities were recorded while travelling in a vehicle, rather than walking the road length which would have improved detection (Slater, 2002). It is also possible that the detectability of carcasses may diminish in areas with dense vegetation adjacent to the road.

Of the feral animals killed, almost 90% were rabbits in any given year. The breakdown of the wallaby grouping shows that swamp wallabies (*W. bicolor*) fatalities were consistently around 20 per year while those of red-necked wallabies (*M. rufogriseus*) fluctuated among years. A large increase in eastern grey kangaroos, wallabies and wombats killed in 2003 was documented and one possible explanation for this may be the drought conditions experienced in this year, creating pressure on animals to cross the highway to find water and forage along the dam edge. Interestingly this increase did not occur among feral animals and birds.

3.3. Spatial clustering

Fatalities of *M. giganteus* occurred over almost the entire length of road. Despite this, the kernel density analysis was able to highlight segments of road with higher density estimates than other sections (Fig. 3(a)).

Table 1
Frequency of animals killed along the Snowy Mountain Highway between Tumut and Talbingo (1998–2003)

Year	Eastern grey kangaroo	Wallabies		Wombats	Feral animals				Birds	Total
		Swamp wallaby	Red-necked wallaby		Rabbit	Fox	Cat	Other		
1998	411	21	20	16	171	8	2	3	88	740
1999	327	21	8	27	182	7	5	5	105	687
2000	381	24	25	23	163	13	3	2	92	726
2001	354	14	9	17	163	9	5	6	121	698
2002	410		28	29		102			110	679
2003	646		51	54		103			80	934
Total	2529		221	166		952			596	4464

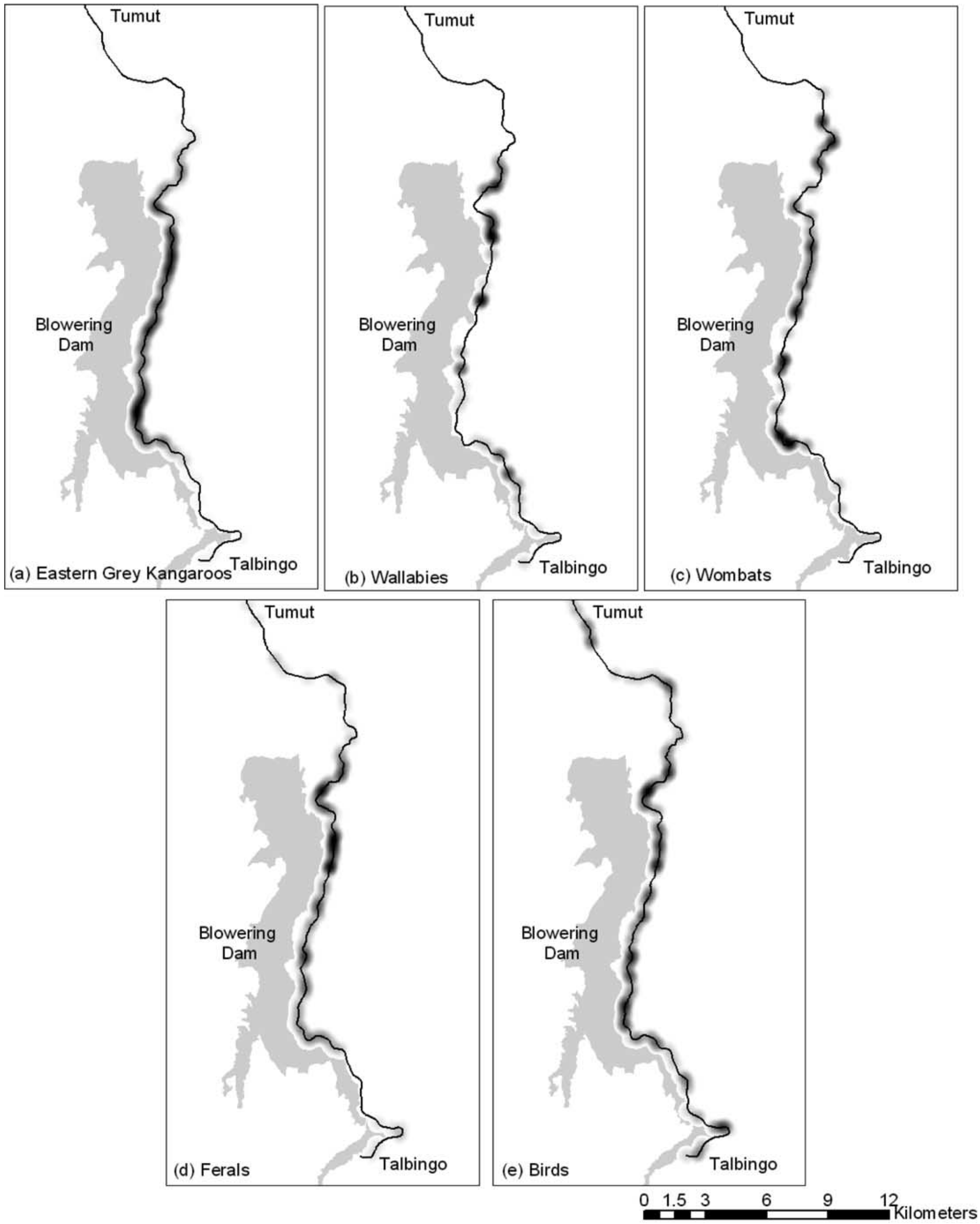

Fig. 3. Kernel density estimates of presence only data, using a bandwidth of 500 m for each of species. Regions of higher density are reflected by darker shading.

Examining the *L*-statistic for *M. giganteus* indicated that clustering of fatalities occurred at scales of up to 10 km, reflecting the high abundance of fatalities occurring adjacent to Blowering Dam (Fig. 4(a)). For wallabies, clusters were identified at a number of short segments of road (Fig. 3(b)) and the locations of these hotspots were randomly distributed at distances greater than 5 km (Fig. 4(b)). While a number of hotspots of *V. ursinus* fatalities were identified, one dense hotspot was located on a bend at around 30 km from Tumut (Fig. 3(c)). The distribution of hotspots clustered at scales of 10 km, similar to the finding for *M. giganteus* (Fig. 4(c)). Two dense hotspots of fatalities of feral animals occurred at around 15 km from Tumut, roughly half-way between Tumut and Talbingo (Fig. 3(d)). Interestingly this segment of road is one of the straightest of the road sections included in this study. Clustering patterns were similar to *M. giganteus* and *V. ursinus* (Fig. 4(d)). For birds, fatalities were more evenly distributed across the length of road directly adjacent Blowering Dam (Fig. 3(e)), and

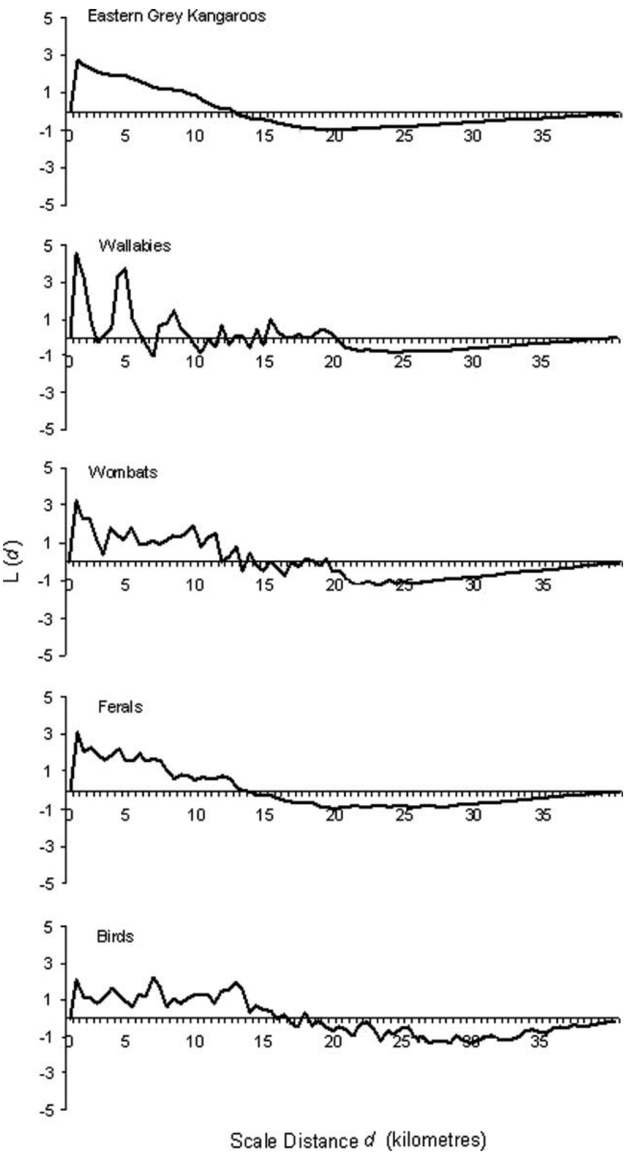

Fig. 4. Plotted values of the L statistic for the network K-function analysis for each species. The L statistic is the difference between the observed K-function values and the values that would be expected if the points were randomly distributed along the network.

this pattern was reflected in the L-statistic which indicated small levels of clustering at scales of up to 10 km.

3.4. Fatality models

3.4.1. *Macropus giganteus*

Of the 10 initial predictors the model selection process recommended a subset of six predictors of *M. giganteus* fatalities (Table 2). There were only three models within one standard error of the model with the highest area under the curve of which the six predictors were in each. The area under the curve suggests that this model only had reasonable support, while the percentage of deviance explained by the model was 23.6% (Table 3). Fatalities of *M. giganteus* were negatively correlated with slope, rainfall over six months, the southern oscillation index, the distance to water and the proportion of forest (Table 4). Only distance from town was positively correlated with fatality probability. Hierarchical partitioning indicated that the most explanatory variables were distance to water and the distance to town, while the proportion of forest had some explanatory power. Of the variables not included in the final model, elevation was found to explain 13.5% of the variation in the response and could have been considered for inclusion in the final model.

3.4.2. Wallabies

For the combined category of wallabies, including both *W. bicolor* and *M. rufogriseus*, there were 16 models with area under the curves within one standard error of the best candidate model (Table 2). The best model in the set was also the most parsimonious (with only three predictors) and was chosen as the final model. The area under the curve was reasonable, suggesting that the model was a satisfactory predictor of wallaby fatalities (Table 3). Rainfall was negatively associated with wallaby fatalities, while forest and distance to town were positively associated with wallaby fatalities (Table 4). The proportion of forest was by far the biggest contributor to the total explained variation in fatalities. The hierarchical partitioning analysis also identified that elevation and distance to water were contributing to fatality probability (23.1% and 12.0%, respectively), but these factors were not identified by the modelling selection process.

3.4.3. *Vombatus ursinus*

There were seven model combinations with area under the curve values within one standard error of the best candidate model for predicting *V. ursinus* fatalities, with the most parsimonious of these included six predictor variables (Table 2). All six predictors were present in each of the seven best models. The discrimination ability of the model to predict *V. ursinus* fatalities was fairly low and the explained deviance was only 11% (Table 3). The southern oscillation index, the distance to water and elevation were negatively associated with fatalities of *V. ursinus*, while slope, sinuosity over 250 m and distance to town were positively associated with fatalities (Table 4). There was good agreement with the selected variables indicated by the hierarchical partitioning, with distance to town and sinuosity contributing most to fatality probability.

3.4.4. Feral animals

The model selection procedure identified 26 models with values of area under the curve within one standard error of the best candidate model for predicting feral animal fatalities (mostly *O. cuniculus*) (Table 2). Only

Table 2
Model selection of all subsets for fatalities of the eastern grey kangaroo, wallabies, the common wombat, feral animals and birds along the Snowy Mountain Highway between Tumut and Talbingo, New South Wales, Australia) and SE/NW modified aspect (A)

Species	Total # models	S	SIN	R	SOI	T	G	W	E	F	A	Median # variables	AUC	
													Mean	SE
Eastern grey kangaroo	3	3	1	3	3	3	1	3	0	3	0	7	0.791	0.001
Wallabies	16	3	0	10	7	16	5	6	0	16	0	4	0.851	0.008
Common wombat	7	7	7	3	7	7	3	7	7	0	3	7	0.766	0.003
Feral animals	26	0	13	25	14	26	10	26	14	13	0	5	0.864	0.004
Birds	29	10	4	29	29	29	26	23	10	14	17	7	0.668	0.005

Values for each variable in the table are the number of times that variable was included in a subset of models within one standard error of the model with the highest area under the roc curve (AUC), including the median number of variables per model in the best model set. Symbols for predictor variables occurring in best model set are slope (S), sinuosity (SIN[a]), rainfall (R[a]), southern oscillation index (SOI[a]), distance to nearest town (T), distance to nearest gully (G), distance to water (W), elevation (E), forest (F[b]). and SE/NW modified aspect (A).

[a] Values for SIN, R and SOI were either one, three or six months, differing among species.

[b] Values for feral animals and birds were distance to nearest forest rather than proportion within home range distance.

Table 3
Deviance explained by the final model for each species using the complete data set with degrees of freedom in brackets along with the area under the curve (AUC)

Species	Predictors	Deviance		% Deviance	AUC
		Null	Residual	Explained	
Eastern grey kangaroo	S + R6 + SOI6 + T + W + F	2961.1 (2135)	2261.5 (2129)	23.6	0.794
Wallabies	R3 + T + F	783.3 (2135)	606.32 (2132)	22.5	0.858
Common wombat	S + SIN250 + SOI6 + T + W + E	777.2 (2135)	691.9 (2129)	11.0	0.778
Feral animals	R1 + T + W	1455.2 (2135)	1038.5 (2132)	28.6	0.872
Birds	R1 + SOI1 + T + G + W	1314.3 (2135)	1243.5 (2130)	5.4	0.672

Symbols for predictor variables are slope (S), sinuosity (SIN*), rainfall (R*), southern oscillation index (SOI), distance to nearest town (T), distance to nearest gully (G), distance to water (W), elevation (E), forest (F) and SE/NW modified aspect (A). For rainfall and southern oscillation index, the numbers after the symbol indicate the number of months over which the values were calculated, while for sinuosity the value after the symbol indicates the distance (m) over which the value was calculated.

three predictors were retained in the final model. Predictive confidence in the feral animal fatality model was high, indicating that the model had good accuracy, while explained deviance was almost 30% (Table 3). Rainfall over one month and distance to water were both negatively associated with feral animal fatalities, while distance to town was positively associated with feral animal fatalities (Table 4). By far the most contribution to explained variation was from distance to town.

3.4.5. Birds

There were 29 models with values of area under the curve within one standard error of the best candidate model for predicting bird fatalities (Table 2). The final model chosen had five predictors, however given a very low value of explained deviance and a poor area under the curve, the explanatory power of the model was weak (Table 3). Rainfall over one month and distance to water were both negatively associated with bird fatalities, while the southern oscillation index, distance to town and distance to gullies were positively associated with bird fatalities (Table 4). The results of the hierarchical partitioning suggest that rainfall contributed most to the small amount of variation explained by the model.

3.5. Model implementation

The probability distributions of fatalities for each species/group were calculated from the models (Fig. 5). For *M. giganteus* one hotspot of eight km in length was observed at the 15–23 km mark from Tumut (Table 5), although fatalities did occur over the entire length of road. Despite only covering 21% of the road length this hotspot accounted for almost 50% of fatalities over the study period. Similarly located but larger in size was the hotspot identified for wallabies. The probability of a fatality occurring at any point along the road during the study period was not particularly high, with an average probability within the hotspot only 0.140. As the proportion of forest had a large effect within the model and values for forest varied on a finer scale than most of the other predictors, the predicted probabilities for wallabies varied considerably at the 10-m scale. Nevertheless, despite the large size of the hotspot over 65% of fatalities recorded occurred within it. In comparison, although there was also substantial variation in predicted probabilities for *V. ursinus*, the use of the top 90th percentile of values enabled the identification of seven small hotspots that could be targeted for mitigation. It is also possible that, depending on the mitigation strategy employed, the

Table 4
Variable coefficients, standard errors and Z-scores for the final models for each species

Species	Variable	Coefficient	SE	Z	P	Independent contribution
Eastern grey kangaroos	Constant	0.1306	0.2416	0.540	0.559	
	S	−0.0351	0.0109	−3.229	0.001	1.89
	R6	−0.0023	0.0004	−6.123	<0.001	5.38
	SOI6	−0.0438	0.0158	−2.770	0.006	1.97
	T	0.0002	0.0001	13.138	<0.001	26.06
	W	−0.0009	0.0001	−13.888	<0.001	37.69
	F	−0.0126	0.0023	−5.399	<0.001	5.59
Wallabies	Constant	−7.8310	0.5644	−13.875	<0.001	
	R3	−0.0028	0.0011	−2.478	0.013	3.26
	T	0.0003	0.0001	9.009	<0.001	12.88
	F	4.5930	0.4655	9.846	<0.001	36.10
Common wombats	Constant	−12.950	2.1590	−6.000	<0.001	
	S	0.0392	0.0212	1.853	0.064	14.96
	S250	10.420	2.1040	4.951	<0.001	19.11
	SOI6	−0.0871	0.0344	−2.533	0.011	6.46
	T	0.0002	0.0001	5.227	<0.001	27.23
	W	−0.0003	0.0001	−3.452	<0.001	13.38
	E	−0.0075	0.0035	−2.126	0.033	8.42
Feral animals	Constant	−3.3993	0.2297	−14.798	<0.001	
	R1	−0.0063	0.0018	−3.537	<0.001	2.19
	T	0.0003	<0.0001	14.441	<0.001	53.71
	W	−0.0006	<0.0001	−8.940	<0.001	19.36
Birds	Constant	−2.1540	0.2382	−9.041	<0.001	
	R1	−0.0111	0.0020	−5.566	<0.001	40.91
	SOI1	0.0286	0.0099	2.889	0.004	9.30
	T	0.0001	0.0001	3.708	<0.001	16.62
	G	0.0013	0.0008	1.587	0.112	3.09
	W	−0.0001	0.0001	−2.719	0.007	9.42

The independent contribution of each variable as determined by hierarchical partitioning is presented as a percentage of the total explained variance. Symbols for predictor variables are slope (S), sinuosity (SIN*), rainfall (R*), southern oscillation index (SOI), distance to nearest town (T), distance to nearest gully (G), distance to water (W), elevation (E), forest (F) and SE/NW modified aspect (A). For rainfall and southern oscillation index, the numbers after the symbol indicate the number of months over which the values were calculated, while for sinuosity the value after the symbol indicates the distance (m) over which the value was calculated.

entire length from 11 to 25 km could be targeted for mitigation as one hotspot. For feral animals there was a large peak in the predicted probability of a fatality that increased to a sharp point at 17 km. The use of the 95th percentile of values identified only a small 2 km section of highway as a hotspot however observed fatalities were clustered at much larger scales. Given the low predictive power of the bird model and the almost even distribution of bird fatalities along the road, the distinction of two hotspots should be treated with caution.

4. Discussion

The ability of the predictive models to identify fatality hotspots for the five species or groups of species varied considerably. Given that fatalities of *M. giganteus* occurred over almost the entire length of road the ability of the predictive models to identify small hotspot areas would be unlikely. That said the predictive model was still able to identify a length of road that did have higher fatality rates than the rest of the highway. Given the sheer number of fatalities of *M. giganteus* along this length of road, management of fatalities is inherently problematic. Targeting those areas identified by the smoothing of presence data (24.6% of the road length) would assist with the prevention of 70.6% of the fatalities recorded. This suggests that when fatality locations are distributed widely and frequently over a length of a road, predictive models may have a restricted utility. However, this failure can be rectified by using smoothing functions on presence only data.

In contrast, the predictive modelling approach was successful in identifying fatality hotspots for *V. ursinus*.

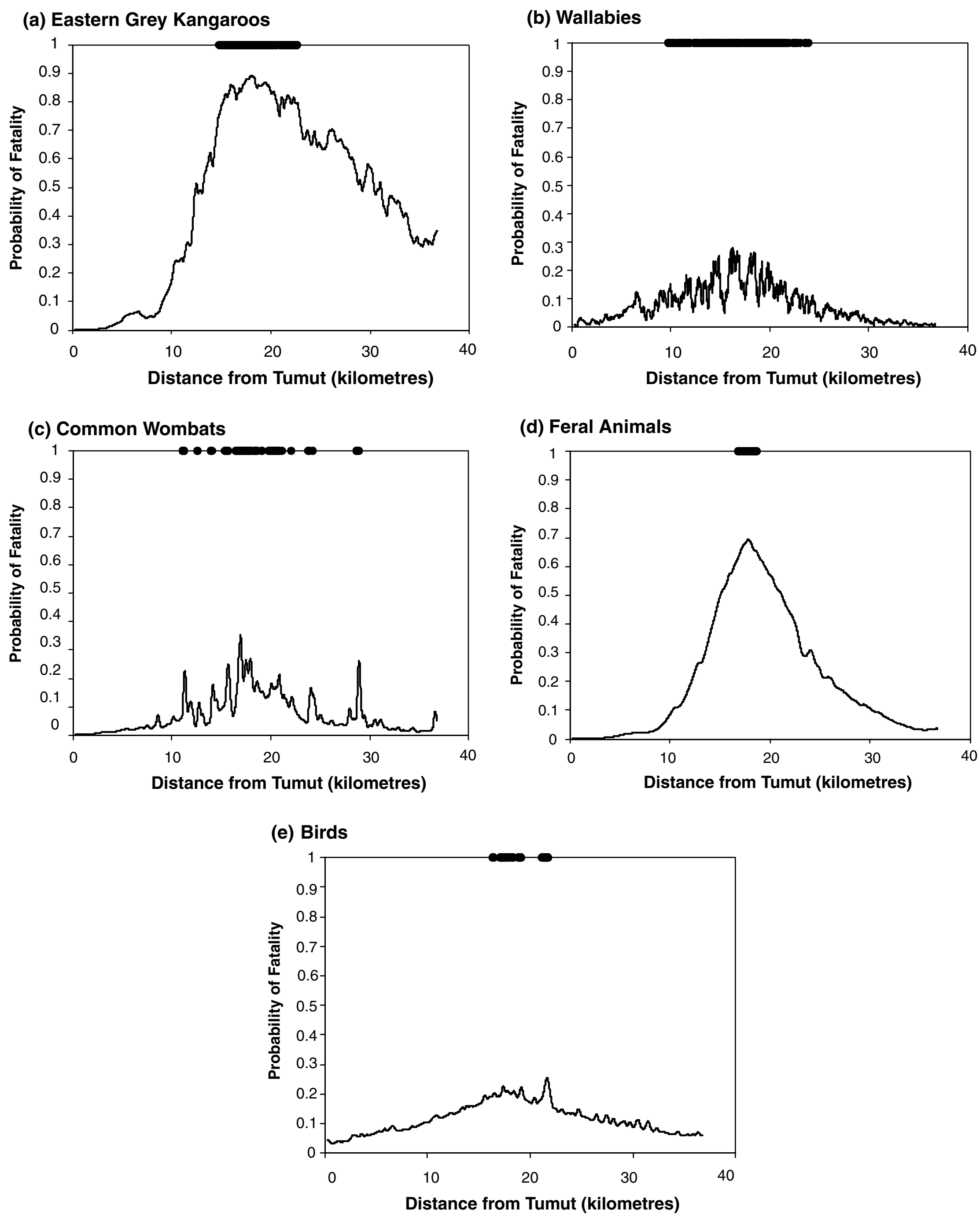

Fig. 5. Distribution of fatality probabilities for each species with increasing distance from Tumut. A moving average of probability over 30 values was used to smooth values estimated on a 10-m scale. The presence of hotspots (values in the top 95th percentile except for wallabies and common wombats where values are the top 90th percentile) are indicated by circles with values of one.

The calculation of the L-statistic confirmed that distinct clumping of fatalities of this species was occurring. The success of the predictive models at identifying these clumps suggests that predictive models may be particularly useful at identifying hotspots of species that possess clumped distributions of fatalities. For wallabies this clumpiness was also evident but as there was considerable scatter of probability values between the 10 and 24 km marks we were not able to distinguish hotspots to reflect this clustering. Along the highway many frequent crossing locations are observable by the creation of trails through the understorey and these typically occur in clusters. These suggest that both wallabies and *V. ursinus* utilise regular crossing points despite the obvious danger.

The predictive modelling approach was successful in identifying explanatory factors contributing to the

Table 5
Hotspots identified by the predictive models for each species along the Snowy Mountain Highway between Tumut and Talbingo

Species	Total kills	Hotspots	Ave. kills	% Kills	Ave. length (km)	% Length	Frequency (km)	Probability
Eastern grey kangaroo	1068	1	506	47.4	8.10	21.4	0.02	0.832
Wallabies	96	1	64	66.7	14.47	39.3	0.23	0.140
Common wombat	95	7	5.3 (1.2)	38.9	0.87 (0.28)	16.5	0.17 (0.03)	0.187 (0.010)
Feral animals	229	1	33	14.4	1.89	5.1	0.06	0.670
Birds	197	2	10.5 (8.5)	10.7	1.74 (1.11)	6.2	0.23 (0.08)	0.221 (0.016)

Data presented are the total kills observed on the road over 22 months between 2002 and 2003, the number of hotspots identified, the average kills observed per hotspot, the percentage of the observed total kills accounted for by the hotspots, the average length of each hotspot, the percentage of the total length of the road accounted for by the hotspots (total 36.78 km), the average frequency of kills observed per hotspot and the average probability of a fatality occurring during the study period at each hotspot. Standard errors are presented in brackets where appropriate.

likelihood of fatalities along the highway. Of the temporal variables included in the study, rainfall was a contributor to the models of most species, although its inclusion did not appear to add much explanatory power (except for birds). The southern oscillation index was retained in three of the species models, but like rainfall also did not have much explanatory power. Finer temporal scale modelling was not possible in this study as we did not know the time of collision of each fatality, but it is likely that the majority of fatalities occurred at night as most species are crepuscular/nocturnal. Some efforts have been made to assess both diurnal and seasonal affects on fatalities (Romin and Bissonette, 1996a; Inbar and Mayer, 1999; Joyce and Mahoney, 2001; Inbar et al., 2002), but overall it is difficult to infer temporal patterns at large scales and most success with evaluating temporal variation has been achieved at small spatial scales (Klöcker, 2003; Lee et al., 2004). Interestingly, the importance of temporal variation for *M. giganteus* and *V. ursinus* fatalities occurred at the six month scale, while for birds and feral animals the one month scale was more important.

Spatial factors contributed most to the variation in the probability of fatalities although just which factors were important differed among species. Distance to town and distance to water contributed to the final models of most species and tended to explain most of the variation. It is apparent that the system used in this study is somewhat biased towards these variables as the majority of kills occurred half-way between the two townships, and this is also where the dam is closest to the road. However this situation is not uncommon and the ability of the models to predict fatalities along other stretches of road remains an important task for future research. Two possible explanations for the positive relationship between fatalities and distance from town might be the result of driver behaviour (e.g. inattention, increased likelihood to speed) or the increase in the abundance of wildlife beyond urban influences. We are currently unable to separate these possibilities.

What was clearer however was that most species, particularly *M. giganteus*, were likely to cross the road from the sheltering forest in the east to access water and grassland adjacent to Blowering Dam in the west, thus explaining the increased probability of fatalities with decreasing proximity to water (namely the dam). Another important spatial predictor was the proportion of forest adjacent to the road. The negative association of the proportion of forest surrounding each fatality for *M. giganteus* and the positive association for wallabies likely reflects preferred foraging habitat. *M. giganteus* are primarily grazers, preferring open grassland for foraging (Coulson, 1999; Ramp and Coulson, 2002), while wallabies are principally browsers (Jarman and Phillips, 1989), preferring understorey shrubs and herbs in the cover of forest. The sinuosity of the road over 250 m was also an important predictor of *V. ursinus* fatalities, suggesting that the often cited indifference of these species to oncoming vehicles may make them more susceptible to collisions when drivers do not have as much vision of the road ahead, and accordingly have less time to take appropriate action to prevent the collision. Behavioural information such as this is useful and highlights the need to have species-specific approaches to management.

Using the knowledge of hotspot locations along the highway and those contributing factors will enable road managers to target fatalities of wildlife. The first step in this process will be to utilise the knowledge of those predictor variables explaining variation in fatality probability identified by the modelling process to develop species-specific management actions. In addition, the next logical step would be to investigate the applicability of the predictive models to surrounding road environments. Fatality information collected on these roads will be necessary to validate the current predictive models and improve their predictive capacity.

4.1. Predictive modelling of fatality hotspots

The modelling of wildlife fatality data to predict the likelihood of fatalities across a range of spatial scales has been accomplished with some success. Typically, roads are divided into segments of varying lengths and the number of road fatalities for each segment tallied for the period of the study. For example, across 43 counties in the US, Finder et al. (1999) used segments of 1.3 km to define fatality hotspots (described as = 15 deer–vehicle accidents in a five year period), while Nielsen et al. (2003) used 0.5 km segments to define fatality hotspots (deer–vehicle accidents = 2) within a 98 km^2 urban area. Recently, both Saeki and Macdonald (2004) and Malo et al. (2004) have developed predictive models using 0.1 km road segments, with Malo et al. (2004) contrasting prediction at this local scale with that at a landscape scale of 1 km segments. The use of road segments contrasts to those studies assessing fatalities at point locations (Clevenger et al., 2003). Most predictive modelling has used binary logistic regression to assess the probability of fatalities in any given road segment, where data reflect either presence/absence of fatalities or high/low numbers of fatalities. Poisson regression of fatality counts per segment has also been conducted (Malo et al., 2004). Problematic in all of these approaches when using binary data is the categorization of fatality absences. Where datasets are comprised of presence only values, absence values are inferred from locations on roads where no fatalities were recorded with varying degrees of precision, typically obtained by randomly choosing road segments at a certain distance from presence/hotspot locations as recorded during the study period (Finder et al., 1999; Nielsen et al., 2003; Malo et al., 2004; Saeki and Macdonald, 2004). In addition, it can be difficult to determine the proportion of fatalities that occurred but were not recorded as quality control and inter-observer reliability is poor (e.g. data from secondary sources such as police and insurance agencies), or the time between sampling periods (i.e. the longevity of carcasses) and observer expertise are not properly quantified. We avoided these problems with the use of a trained observer and a regular sampling regime.

Given model selection uncertainty, a primary concern when developing predictive models is the recognition that no single model represents the true relationship between predictor variables and the location of wildlife fatalities (Burnham and Anderson, 2002). Many studies have implemented stepwise procedures on upwards of 30 variables to derive a final predictive model of wildlife fatalities. Stepwise regression has inherent deficiencies compounded by the use of many probably correlated variables (Mac Nally, 2000; Boyce et al., 2002; Burnham and Anderson, 2002). A more appropriate solution is to define a set of a priori predictors, inferring biological relevance at the scale in question. There may be many variables that influence the likelihood of a collision at a given location, but it does not necessarily follow that these variables are useful in a predictive model of hotspot locations. Model selection can then be performed on these predictors to derive a final model that provides adequate predictive power.

4.2. Mitigation of fatalities at hotspots

Much effort has been spent examining the effectiveness of various mitigation strategies world-wide (Waring et al., 1991; Groot Bruinderink and Hazebroek, 1996; Romin and Bissonette, 1996b). Australia's larger marsupial herbivores differ from their placental counterparts elsewhere and as such need tailored preventative measures to suit them. For the most part they are non-migratory; typically have high site fidelity and posses relatively small home ranges (Strahan, 2002). Thus mitigation strategies employed for migratory deer in Europe, the US and Canada may not be effective for preventing wildlife fatalities under Australian conditions. Some research in Australia has examined common strategies such as the installation of fences to prevent movement of wildlife and the installation of underpasses to facilitate the safe passage of wildlife (Mansergh and Scotts, 1989; Australian Museum Business Services, 1997; Jones, 2000; Abson and Lawrence, 2003; Taylor and Goldingay, 2003). These studies report various levels of success. Using the hotspots we have identified, particularly those for *V. ursinus*, it is possible that the installation of underpasses at those locations may have a significant cost-benefit. Indeed we have observed some individuals of *V. ursinus* utilising pre-existing culverts in order to regularly cross the road.

Strategies have also been developed to target those animals within the vicinity of roads, such as the use of reflectors designed to reflect oncoming vehicle headlights into animals to frighten them before the vehicle arrives (e.g. wildlife warning reflectors, Strieter Corporation, 2001), and the development of sound devices attached to vehicles to again frighten animals away before collision distance is reached (e.g. Shu Roo wildlife dispersal systems, Shu Roo Australia Pty Ltd.). Recent research suggests that neither the reflectors (Lintermans, 1997) nor the Shu Roos (Bender, 2001) have any preventative effect. New approaches to reduce the amount of time spent by animals on the roadside seek to exploit the innate fear of predators through scent (Ramp et al., 2005) and could prove fruitful if combined with verge modification (E. Lee, unpublished data), but any reduction of fatalities may only be transient.

4.3. Conclusion

Identification of fatality hotspots is an important first step to mitigating the fatalities of wildlife on roads. Combining the spatial clustering and predictive modelling enabled a solid corroborative approach to evaluating the distribution and patterning of wildlife fatality hotspots along the Snowy Mountain Highway in southern New South Wales. We suggest that kernel density estimation is an appropriate approach to identifying hotspots where presence data exists for all target roads. Where the intention is to extrapolate to additional or larger areas with similar characteristics, presence/absence data are necessary to develop predictive models. Once fatality hotspots are identified for different species in different regions, these areas become prime targets for implementing mitigation strategies and assessing the impact of roads on local wildlife populations. The development of predictive models also enables the identification of explanatory factors and this assists with the development of species-specific management strategies. What these models do not tell us are why animals are crossing the road more frequently at these locations and what effect the fatalities are having on the dynamics of population adjacent to roads. Given the high number of fatalities recorded it is likely that the habitat surrounding the road may be acting as a sink and this question is currently being addressed by our continuing research.

Acknowledgements

Recognition must go to the numerous WIRES volunteers that assisted JC with the collection of fatality information over the years. Thanks also to Rob Keskull of GPS Data Loggers for custom-designing the five-button data loggers. This research was supported by the Australian Research Council (grant LP0346925, APDI to DR), the International Fund for Animal Welfare, the New South Wales Department of Environment and Conservation (National Parks and Wildlife Division), the New South Wales Wildlife Information and Rescue Service and Roe Koh & Associates Pty Ltd.

Appendix 1

Species list of both native (N) and feral (F) animals recorded as killed along the Snowy Mountain Highway between Tumut and Talbingo (1998–2003). Nomenclature follows Strahan (2002) for mammals, Christidis and Boles (1995) for birds, and Cogger (2000) for reptiles

Type	Species name	Scientific name	Status
Avifauna	Yellow Thornbill	*Acanthiza nana*	N
Avifauna	Eastern Spine Bill	*Acanthorhynchus tenuirostris*	N
Avifauna	Brown Goshawk	*Accipiter fasciatus*	N
Avifauna	Australian King Parrot	*Alisterus scapularis*	N
Avifauna	Wedged Tailed Eagle	*Aquila audax*	N
Avifauna	White-faced Heron	*Ardea novaehollandiae*	N
Avifauna	Sulphur Crested Cockatoo	*Cacatua galerita*	N
Avifauna	Galah	*Cacatua roseicapilla*	N
Avifauna	Gang-gang Cockatoo	*Callocephalon fimbriatum*	N
Avifauna	European Goldfinch	*Carduelis carduelis*	F
Avifauna	Australian Wood Duck	*Chenonetta jubata*	N
Avifauna	Australian Raven	*Corvus coronoides*	N
Avifauna	Kookaburra	*Dacelo novaeguineae*	N
Avifauna	Emu	*Dromaius novaehollandiae*	N
Avifauna	Peregrine Falcon	*Falco peregrinus*	N
Avifauna	Australian Magpie	*Gymnorhina tibicen*	N
Avifauna	Welcome Swallow	*Hirundo neoxena*	N
Avifauna	Yellow-faced Honeyeater	*Lichenostomus chrysops*	N
Avifauna	Superb Fairy Wren	*Malurus cyaneus*	N
Avifauna	Barking Owl	*Ninox connivens*	N
Avifauna	Southern Boobook Owl	*Ninox novaeseelandiae*	N
Avifauna	Spotted Pardalote	*Pardalotus punctatus*	N
Avifauna	Striated Pardalote	*Pardalotus striatus*	N
Avifauna	Flame Robin	*Petroica phoenicea*	N
Avifauna	New Holland Honeyeater	*Phylidonyris novaehollandiae*	N
Avifauna	Crimson Rosella	*Platycerus elegans*	N
Avifauna	Red-rumped Parrot	*Psephotus haematonotus*	N
Avifauna	Diamond Fire-tail Finch	*Steganopleura guttata*	N
Avifauna	Pied Currawong	*Strepa graculina*	N
Avifauna	Common Starling	*Sturnus vulgaris*	F
Marsupial	Dusky Antechinus	*Antechinus swainsonii*	N
Marsupial	Southern Brown Bandicoot	*Isoodon obesulus*	N
Marsupial	Eastern Grey Kangaroo	*Macropus giganteus*	N

(*continued on next page*)

Appendix 1 (*continued*)

Type	Species name	Scientific name	Status
Marsupial	Euro	*Macropus robustus*	N
Marsupial	Red-necked Wallaby	*Macropus rufogriseus*	N
Marsupial	Bush Rat	*Rattus fuscipes*	N
Marsupial	Brushtail Possum	*Trichosurus vulpecula*	N
Marsupial	Bat	*Unknown*	N
Marsupial	Common Wombat	*Vombatus ursinus*	N
Marsupial	Swamp Wallaby	*Wallabia bicolor*	N
Monotreme	Platypus	*Ornithorhynchus anatinus*	N
Monotreme	Short-beaked Echidna	*Tachyglossus aculeatus*	N
Placental	Domestic Dog	*Canis lupus familiaris*	F
Placental	Cat	*Felis catus*	F
Placental	Brown Hare	*Lepus capensis*	F
Placental	House Mouse	*Mus musculus*	F
Placental	European Rabbit	*Oryctolagus cuniculus*	F
Placental	Pig	*Sus scrofa*	F
Placental	Red Fox	*Vulpes vulpes*	F
Reptile	Highland Copperhead Snake	*Austrelaps ramsayi*	N
Reptile	Red-bellied Black Snake	*Pseudechis porphyriacus*	N
Reptile	Eastern Brown Snake	*Pseudonaja textilis*	N
Reptile	Eastern Blue-tongue Lizard	*Tiliqua scincoides*	N
Reptile	Rosenberg's Goanna	*Varanus rosenbergi*	N

References

Abson, R.N., Lawrence, R.E., 2003. Slaty creek wildlife underpass study. Centre for Sustainable Regional Communities, La Trobe University Bendigo, Australia.

Ahrens, C.D., 1991. Meteorology Today: An Introduction to Weather, Climate, and the Environment. West Publishing, Minnesota.

Andrews, A., 1990. Fragmentation of habitat by roads and utility corridors: a review. Australian Zoologist 26, 130–141.

Australian Museum Business Services, 1997. Fauna usage of three underpasses beneath the F3 Freeway between Sydney and Newcastle. Australian Museum Business Services Consulting & Roads and Traffic Authority, Sydney.

Baker, P.J., Harris, S., Robertson, C.P.J., Saunders, G., White, P.C.L., 2004. Is it possible to monitor mammal population changes from counts of road traffic casualties. An analysis using Bristol's red foxes *Vulpes vulpes* as an example? Mammal Review 34, 115–130.

Bashore, T.L., Tzilkowski, W.M., Bellis, E.D., 1985. Analysis of deer–vehicle collision sites in Pennsylvania. Journal of Wildlife Management 49, 769–774.

Beers, T.W., Dress, P.E., Wensel, L.C., 1966. Aspect transformation in site productivity research. Journal of Forestry 64, 691–692.

Bender, H., 2001. Deterrence of kangaroos from roadways using ultrasonic frequencies – efficacy of the Shu Roo. University of Melbourne, Melbourne, Australia.

Bennett, A.F., 1991. Roads, roadsides and wildlife conservation: a review. In: Saunders, D.A., Hobbs, R.J. (Eds.), Nature Conservation 2: The Role of Corridors. Surrey Beatty & Sons, Chipping, Norton, pp. 99–117.

Beyer, H.L., 2004. Hawth's Analysis Tools for ArcGIS. Available from: <http://www.spatialecology.com/htools>.

Boyce, M.S., Vernier, P.R., Nielsen, S.E., Schmiegelow, F.K.A., 2002. Evaluating resource selection functions. Ecological Modelling 157, 281–300.

Brown, B.C., 2001. Marsupial roadkill on the Kosciuszko Road in the Australian Alps: an investigation of factors influencing animal–vehicle collisions. Honours, The Australian National University.

Burnham, K.P., Anderson, D.R., 2002. Model selection and multimodel inference.A Practical Information–Theoretic Approach Springer, New York.

Christidis, L., Boles, W.E., 1995. Taxonomy and Species of Birds of Australia and its Territories. Royal Australasian Ornithologists Union, Melbourne, Australia.

Clevenger, A.P., Chruszcz, B., Gunson, K.E., 2003. Spatial patterns and factors influencing small vertebrate fauna road-kill aggregations. Biological Conservation 109, 15–26.

Cogger, H.G., 2000. Reptiles and Amphibians of Australia. Reed New Holland, Sydney, Australia.

Cooper, D.W., 1998. Road kills of animals on some New South Wales roads. Report on data collected by WIRES volunteers in 1997. Macquarie University Sydney.

Coulson, G., 1997. Male bias in road-kills of macropods. Wildlife Research 24, 21–25.

Coulson, G., 1999. Monospecific and heterospecific grouping and feeding behavior in grey kangaroos and red-necked wallabies. Journal of Mammalogy 80, 270–282.

Coulson, G.M., 1982. Road-kills of macropods on a section of highway in central Victoria. Australian Wildlife Research 9, 21–26.

Coulson, G.M., 1989. The effect of drought on road mortality of macropods. Australian Wildlife Research 16, 79–83.

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

Driessen, M.M., Mallick, S.A., Hocking, G.J., 1996. Habitat of the eastern barred bandicoot, *Perameles gunnii*, in Tasmania – an analysis of road-kills. Wildlife Research 23, 721–727.

Dyer, S.J., O'Neill, J.P., Wasel, S.M., Boutin, S., 2002. Quantifying barrier effects of roads and seismic lines on movements of female woodland caribou in northeastern Alberta. Canadian Journal of Zoology 80, 839–845.

Ellenberg, H., Muller, K., Stottele, T., 1981. Strassen-Okologie: Auswirkun-gen von Autobahnen und Strasse auf Okosysteme deutscher Landschaften. Okologie und Strasse. Broschurenreihe der Deutschen Strassenliga, Ausgabe 3, Bonn. pp. 19–122.

Federal Highway Administration, 1996. Evaluation and Management of Highway Runoff Water Quality. Publication FHWA-PD-96-032. US Department of Transportation, Washington, DC.

Ferrier, S., Watson, G., Pearce, J., Drielsma, M., 2002. Extended statistical approaches to modelling spatial pattern in biodiversity in northeast New South Wales. I. Species-level modelling. Biodiversity and Conservation 11, 2275–2307.

Fielding, A.H., Bell, J.F., 1997. A review of methods for the assessment of prediction errors in conservation presence/absence models. Environmental Conservation 24, 38–49.

Finder, R.A., Roseberry, J.L., Woolf, A., 1999. Site and landscape conditions at white-tailed deer–vehicle collision locations in Illinois. Landscape and Urban Planning 44, 77–85.

Forman, R.T.T., Alexander, L.E., 1998. Roads and their major ecological effects. Annual Review of Ecology and Systematics 29, 207–231.

Forman, R.T.T., Reineking, B., Hersperger, A.M., 2002. Road traffic and nearby grassland bird patterns in a suburbanizing landscape. Environmental Management 29, 782–800.

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

Gattrell, A.C., Bailey, T.C., Diggle, P.J., Rowlingsont, B.S., 1996. Spatial point pattern analysis and its application in geographical epidemiology. Transactions of the Institute of British Geographers 21, 256–274.

Gerlach, G., Musolf, K., 2000. Fragmentation of landscape as a cause for genetic subdivision in bank voles. Conservation Biology 14, 1066–1074.

Gibson, L.A., Wilson, B.A., Aberton, J.G., 2004a. Landscape characteristics associated with species richness and occurrence of small mammals inhabiting a coastal heathland: a spatial modelling approach. Biological Conservation 120, 75–89.

Gibson, L.A., Wilson, B.A., Cahill, D.M., Hill, J., 2004b. Modelling habitat suitability of the swamp antechinus (*Antechinus minimus maritimus*) in the coastal heathlands of southern Victoria, Australia. Biological Conservation 117, 143–150.

Gibson, L.A., Wilson, B.A., Cahill, D.M., Hill, J., 2004c. Spatial prediction of rufous bristlebird habitat in a coastal heathland: a GIS-based approach. Journal of Applied Ecology 41, 213–223.

Goosem, M., 2001. Effects of tropical rainforest roads on small mammals: inhibition of crossing movements. Wildlife Research 28, 351–364.

Goosem, M., 2002. Effects of tropical rainforest roads on small mammals: fragmentation, edge effects and traffic disturbance. Wildlife Research 29, 277–289.

Groot Bruinderink, G.W.T.A., Hazebroek, E., 1996. Ungulate traffic collisions in Europe. Conservation Biology 10, 1059–1067.

Hastie, T., Tibshirani, R., Friedman, J.H., 2001. The Elements of Statistical Learning. Springer-Verlag, New York.

Hubbard, M.W., Danielson, B.J., Schmitz, R.A., 2000. Factors influencing the location of deer–vehicle accidents in Iowa. Journal of Wildlife Management 64, 707–713.

Inbar, M., Mayer, R.T., 1999. Spatio-temporal trends in armadillo diurnal activity and road-kills in central Florida. Wildlife Society Bulletin 27, 865–872.

Inbar, M., Shanas, U., Izhaki, I., 2002. Characterization of road accidents in Israel involving large mammals. Israel Journal of Zoology 48, 197–206.

Jarman, P.J., Phillips, C.M., 1989. Diets in a community of macropod species. In: Grigg, G., Jarman, P., Hume, I. (Eds.), Kangaroos, Wallabies and Rat-kangaroos. Surrey Beatty, New South Wales, pp. 143–149.

Johnson, C.N., 1987. Macropod studies at Wallaby Creek IV. Home range and movements of the red-necked wallaby. Australian Wildlife Research 14, 125–132.

Jones, M.E., 2000. Road upgrade, road mortality and remedial measures: impacts on a population of eastern quolls and Tasmanian devils. Wildlife Research 27, 289–296.

Joyce, T.L., Mahoney, S.P., 2001. Spatial and temporal distributions of moose–vehicle collisions in Newfoundland. Wildlife Society Bulletin 29, 281–291.

Klöcker, U., 2003. An evaluation of factors leading to kangaroo–vehicle collisions in the arid zone of Australia. Graduate Diploma Bonn University, Germany.

Lee, E., Klöcker, U., Croft, D.B., Ramp, D., 2004. Kangaroo–vehicle collisions in Australia's sheep rangelands, during and following drought periods. Australian Mammalogy 26, 215–226.

Lintermans, M., 1997. A review of the use of Swareflex wildlife reflectors to reduce the incidence of road-kills in native fauna. Living with Eastern Grey Kangaroos in the ACT Third Report, Appendix D. ACT Kangaroo Advisory Committee, Canberra.

Mac Nally, R., 2000. Regression and model-building in conservation biology, biogeography and ecology: The distinction between – and reconciliation of – 'predictive' and 'explanatory' models. Biodiversity and Conservation 9, 655–671.

Mac Nally, R., 2002. Multiple regression and inference in ecology and conservation biology: further comments on identifying important predictor variables. Biodiversity and Conservation 11, 1397–1401.

Mallick, S.A., Hocking, G.J., Driessen, M.M., 1998. Road-kills of the eastern barred bandicoot (*Perameles gunnii*) in Tasmania: an index of abundance. Wildlife Research 25, 139–145.

Malo, J.E., Suárez, F., Díez, A., 2004. Can we mitigate animal–vehicle accidents using predictive models? Journal of Applied Ecology 41, 701–710.

Manel, S., Williams, H.C., Ormerod, S.J., 2001. Evaluating presence–absence models in ecology: the need to account for prevalence. Journal of Applied Ecology 38, 921–931.

Mansergh, I.M., Scotts, D.J., 1989. Habitat continuity and social–organization of the mountain pygmy-possum restored by tunnel. Journal of Wildlife Management 53, 701–707.

Moore, B.D., Coulson, G., Way, S., 2002. Habitat selection by adult female eastern grey kangaroos. Wildlife Research 29, 439–445.

Nielsen, C.K., Anderson, R.G., Grund, M.D., 2003. Landscape influences on deer–vehicle accident areas in an urban environment. Journal of Wildlife Management 67, 46–51.

Okabe, A., Okunuki, K., Funamoto, S., 2003. SANET: A toolbox for spatial analysis on a network. Centre for Spatial Information Science, University of Tokyo, Tokyo.

Okabe, A., Yamada, I., 2001. The *K*-function method on a network and its computational implementation. Geographical Analysis 33, 271–290.

Osawa, R., 1989. Road-kills of the swamp wallaby, *Wallabia bicolor*, on North Stradbroke Island, south-east Queensland. Australian Wildlife Research 16, 95–104.

O'Sullivan, D., Unwin, D., 2003. Geographical Information Analysis. Wiley, New York.

Pearce, J., Ferrier, S., 2000. Evaluating the predictive performance of habitat models developed using logistic regression. Ecological Modelling 133, 225–245.

Puglisi, M.J., Lindzey, J.S., Bellis, E.D., 1974. Factors associated with highway mortality of white-tailed deer. Journal of Wildlife Management 38, 799–807.

R Development Core Team, 2005. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Ramp, D., Coulson, G., 2002. Density dependence in foraging habitat preference of eastern grey kangaroos. Oikos 98, 393–402.

Ramp, D., Russell, B.G., Croft, D.B., 2005. Predator scent induces differing responses in two sympatric macropodids. Australian Journal of Zoology 53, 73–78.

Reijnen, R., Foppen, R., Veenbaas, G., 1997. Disturbance by traffic of breeding birds: evaluation of the effect and considerations in planning and managing road corridors. Biodiversity and Conservation 6, 567–581.

Rencher, A.C., 1995. Methods of Multivariate Analysis. Wiley, New York.

Richardson, J.H., Shore, R.F., Treweek, J.R., Larkin, S.B.C., 1997. Are major roads a barrier to small mammals? Journal of Zoology 243, 840–846.

Ripley, B.D., 1976. The second-order analysis of stationary point processes. Journal of Applied Probability 13, 255–266.

Romin, L.A., Bissonette, J.A., 1996a. Temporal and spatial distribution of highway mortality of mule deer on newly constructed roads at Jordanelle Reservoir, Utah. Great Basin Naturalist 56, 1–11.

Romin, L.A., Bissonette, J.A., 1996b. Deer–vehicle collisions – status of state monitoring activities and mitigation efforts. Wildlife Society Bulletin 24, 276–283.

Saeki, M., Macdonald, D.W., 2004. The effects of traffic on the raccoon dog (*Nyctereutes procyonoides viverrinus*) and other mammals in Japan. Biological Conservation 118, 559–571.

Seabrook, W.A., Dettmann, E.B., 1996. Roads as activity corridors for cane toads in Australia. Journal of Wildlife Management 60, 363–368.

Seiler, A., 2004. Trends and spatial patterns in ungulate-vehicle collisions in Sweden. Wildlife Biology 10, 301–313.

Sherwood, B., Cutler, D., Burton, J. (Eds.), 2002. Wildlife and Roads: the Ecological Impact. Imperial College Press, London, UK.

Skerratt, L.F., Skerratt, J.H.L., Banks, S., Martin, R., Handasyde, K., 2004. Aspects of the ecology of common wombats (*Vombatus ursinus*) at high density on pastoral land in Victoria. Australian Journal of Zoology 52, 303–330.

Slater, F.M., 2002. An assessment of wildlife road casualties – the potential discrepancy between numbers counted and numbers killed. Web Ecology 3, 33–42.

Spooner, P.G., Lunt, I.D., Briggs, S.V., 2004. Spatial analysis of anthropogenic disturbance regimes and roadside shrubs in a fragmented agricultural landscape. Applied Vegetation Science 7, 61–70.

Stiles, J.H., Jones, R.H., 1998. Distribution of the red imported fire ant, *Solenopsis invicta*, in road and powerline habitats. Landscape Ecology 13, 335–346.

Strahan, R. (Ed.), 2002. The Mammals of Australia. Reed New Holland, Sydney, Australia.

Strieter Corporation, 2001. Strieter-Lite: Wild Animal Highway Warning Reflector System. Installation Instructions, Rock Island, IL.

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

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

Tikka, P.M., Hogmander, H., Koski, P.S., 2001. Road and railway verges serve as dispersal corridors for grassland plants. Landscape Ecology 16, 659–666.

Troy, S., Coulson, G., 1993. Home range of the swamp wallaby, *Wallabia bicolor*. Wildlife Research 20, 571–577.

Ullmann, I., 1998. Lateral differentiation and the role of exotic species in roadside vegetation in southern New Zealand. Flora 193, 149–164.

van der Ree, R., 2002. The population ecology of the squirrel glider (*Petaurus norfolcensis*) within a network of remnant linear habitats. Wildlife Research 29, 329–340.

van Langevelde, F., Jaarsma, C.F., 2004. Using traffic flow theory to model traffic mortality in mammals. Landscape Ecology 19, 895–907.

Vestjens, W.J.M., 1973. Wildlife mortality on a road in New South Wales. Emu 73, 107–112.

Walsh, C.J., Mac Nally, R., 2003. The hier.part package. Hierarchical Partitioning. R project for statistical computing. Avaialble from: <http://cran.r-project.org/>.

Waring, G.H., Griffs, J.L., Vaughn, M.E., 1991. White-tailed deer roadside behaviour, wildlife warning reflectors, and highway mortality. Applied Animal Behaviour Science 29, 215–223.

White, P.C.L., Newton-Cross, G.A., Gray, M., Ashford, R., White, C., Saunders, G., 2003. Spatial interactions and habitat use of rabbits on pasture and implications for the spread of rabbit haemorrhagic disease in New South Wales. Wildlife Research 30, 49–58.