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Tese de Doutorado

Estratégias de planejamento da mitigação do atropelamento de fauna em rodovias

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ESTRATÉGIAS DE PLANEJAMENTO DA MITIGAÇÃO DO ATROPELAMENTO DE FAUNA EM RODOVIAS

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Resumo

Infraestruturas lineares, como as estradas, estão por todos os lugares no mundo e os impactos causados por elas são inúmeros e intensos. Focando no impacto de mortalidade de fauna por colisão com veículos, esta tese teve o objetivo de propor diferentes abordagens para identificar locais para a implementação de medidas de mitigação desse impacto. Além da introdução geral, a tese tem três capítulos que correspondem a três artigos científicos. O primeiro capítulo explorou dados de répteis atropelados em 33 meses de monitoramento mensais em 277 km da BR-101 e avaliou tanto o padrão espacial quanto o padrão temporal de fatalidades além de estimar a magnitude de atropelamentos de répteis na estrada. O segundo e o terceiro capítulo exploram abordagens preditivas de atropelamento de fauna para dois diferentes contextos: uma única estrada e uma rede de estradas. O segundo capítulo teve o objetivo de testar se usando características da paisagem, da rodovia e dos animais, nós podemos predizer onde estão os locais com maior chance de um animal ser atropelado. Para isso, também para a BR-101, calculei a probabilidade de travessia através de mapas de conectividade e a probabilidade de colisão através de uma equação que considera o tráfego de veículos, o tamanho dos animais e dos veículos e a velocidade dos animais para duas espécies de mamíferos nativos do Brasil: o furão (*Galictis cuja*) e o zorrilho (*Conepatus chinga*). Para o terceiro capítulo, foi utilizado a rede de estradas do estado de Victoria na Austrália, na qual calculei a probabilidade de travessia e de colisão para o canguru cinza oriental (*Macropus giganteus*), espécie nativa da Austrália. No primeiro capítulo, demonstrei que: 15.377 cágados, lagartos e serpentes são atropelados a cada ano na BR-101 no sul do Brasil; *hot moments* de atropelamentos de répteis ocorreram no verão, especialmente em dezembro para lagartos e serpentes; *hotspots* de atropelamentos foram coincidentes para tartarugas, lagartos e serpentes; existiu um efeito positivo do tráfego e da rizicultura nos atropelamentos e negativo da silvicultura; medidas de mitigação nos *hotspots* prioritários poderiam evitar 45% das fatalidades de répteis. No segundo capítulo, concluí que a probabilidade de fatalidade através da multiplicação das probabilidades de travessia e colisão não teve um bom poder de predição dos atropelamentos e que a probabilidade de colisão sozinha foi melhor em predizer os atropelamentos do que a probabilidade de travessia, entretanto as espécies apresentaram padrões diferentes. No terceiro capítulo, concluí que um modelo aditivo das duas probabilidades foi melhor em predizer os atropelamentos de cangurus do que os modelos individuais de probabilidades de travessia e colisão, entretanto o modelo integrado não apresentou a predição esperada. A probabilidade de travessia foi um preditor melhor dos atropelamentos de cangurus que a probabilidade de colisão para a rede de estradas. Portanto, concluo que: 1) os atropelamentos de fauna podem ser bastante acentuados em determinados contextos e que é possível identificar locais de maior agregação que seriam efetivos para mitigação; 2) é possível usar dados de tráfego de veículos e tamanho e velocidade dos animais para predizer locais de mais atropelamentos, entretanto deve se ter cuidado pois isso é específico para cada espécie; 3) para o contexto de rede de estradas, é possível predizer o atropelamento utilizando a probabilidade de travessia e a probabilidade de colisão em um mesmo modelo. Ainda é necessário explorar outras maneiras de calcular e integrar as probabilidades aqui propostas, mas nesta tese eu demonstrei uma forma possível de predizer atropelamentos para um contexto em que não há dados dessa natureza disponíveis, seja para estradas novas ou para uma rede de estradas.

Palavras-chave: colisões animais-veículos, *hotspots* de atropelamento, ecologia da paisagem

Abstract

Linear infrastructures, such as roads, are worldwide and impacts caused by them are innumerable and intense. We focused on impact of road-kills due to wildlife-vehicle collisions and aimed to propose different approaches to identify locations to implement mitigation measures for this impact. Besides the general introduction, this thesis has three chapters which correspond to three scientific papers. The first chapter examined reptile road-kill data from monthly road survey during 33 months in a 277 km of BR-101 road. We evaluated spatial and temporal patterns of road-kills and estimated the magnitude of reptile road-kills on that road. The second and third chapters examined predictive approaches of wildlife road-kills for two different contexts: a single road and a road network. The second chapter aimed to test if it is possible to use of landscape, road, animals features to predict locations where there are more road-kills. For the same road (BR-101), I calculated crossing probability using connectivity maps and collision probability using an equation which considers traffic volume, animal and vehicle size, and animal speed for two native mammal species from Brazil: the Lesser Grison (*Galictis cuja*) and the Molina's Hog-nosed Skunk (*Conepatus chinga*). To the third chapter, I used the road network of Victoria state in Australia, which I calculated crossing and collision probabilities for eastern grey kangaroo (*Macropus giganteus*), a native species from Australia. In the first chapter, I demonstrated that: 15,377 freshwater turtles, lizards and snakes are road-kills each year in Br-101 in Southern Brazil; road-kill *hot moments* occur in the summer, specially in December for lizards and snakes; road-kill *hotspots* are coincident among freshwater turtles, lizards and snakes; there is a positive effect of traffic and rice plantation on road-kills and a negative effect of silviculture; mitigation measures of priority *hotspots* could avoid 45% of reptile fatalities. In the second chapter, I concluded that fatality probability though multiplication of crossing and collision probabilities did not have a good predictive power of road-kills and collision probability alone was better to predict road-kills than crossing probability, however species showed different patterns. In the third chapter, I concluded that an additive model with the two probabilities was better to predict kangaroo road-kills than individual models of crossing and collision probabilities, however the integrated model did not present an expected prediction. Crossing probability was a better predictor of kangaroos road-kills than collision probability for the road network. Therefore, I concluded that: 1) wildlife road-kills can be really high in some contexts and it is possible to identify locations with more road-kill aggregations which would be effective for mitigation; 2) it is possible to use traffic volume, animals size and speed to predict location of road-kills, however it is specific for each species; 3) for road network context, it is possible to predict kangaroo road-kills using crossing and collision probability in the same model. Exploring another ways to calculate and integrate the probabilities used here is necessary, however in this thesis I demonstrated one possible manner to predict road-kills in a context which road-kill are not available, such as new roads or road networks.

Keywords: wildlife-vehicle collisions, road-kill hotspots, landscape ecology

Sumário

Introdução Geral

Rodovias pelo mundo e seus impactos

Rodovias facilitam o movimento de pessoas, por isso têm um importante papel no desenvolvimento econômico e urbano e, assim, fazem-se presentes onde quer que os humanos se estabeleçam. Contudo, a construção de rodovias de todos os tipos e o consequente tráfego afetam os ecossistemas terrestres e aquáticos, direta e indiretamente, de várias maneiras (Figura 1): a perda de habitat devido à construção da estrada, a mortalidade de fauna por atropelamento, a subdivisão de populações através da fragmentação e a inacessibilidade de recursos através do efeito de barreira (VAN DER REE; SMITH; GRILO, 2015). A mortalidade pode ser considerada um dos principais mecanismos diretos a comprometer o tamanho e persistência das populações silvestres (FAHRIG; RYTWINSKI, 2009; JACKSON; FAHRIG, 2011; JAEGER; FAHRIG, 2004) e a identificação dos fatores e ações para diminuir a mortalidade são fundamentais no contexto da conservação da biodiversidade. Segundo Fahrig & Rytwinski (2009), a mortalidade de fauna por atropelamento pode ter efeitos substanciais na densidade populacional, tendo aparentemente uma maior importância para a persistência das populações do que o isolamento por evitamento da rodovia (JACKSON; FAHRIG, 2011). Os atropelamentos de animais silvestres em rodovias são considerados por alguns autores como a principal causa antrópica direta de mortalidade de fauna, ultrapassando até mesmo a caça (FORMAN; ALEXANDER, 1998). Assim, tem-se despendido um esforço imenso em avaliar a magnitude do impacto de atropelamentos sobre a fauna. A contagem dos animais atropelados pode ser útil para avaliar a magnitude do impacto de rodovias, entretanto essa simples contagem é inadequada para entender as relações entre a rodovia e a fauna silvestre (CLEVENGER; CHRUSZCZ; GUNSON, 2003). Diversos trabalhos têm demonstrado que os atropelamentos não ocorrem aleatoriamente ao longo das rodovias, mas que são agregados espacialmente (CLEVENGER; CHRUSZCZ; GUNSON, 2003; COELHO; KINDEL; COELHO, 2008). Por isso, alguns estudos têm priorizado as estimativas de pontos de agregação de atropelamentos ao longo da rodovia com o objetivo principal de propor locais e medidas mais adequadas para mitigar esse impacto.

Estratégias e ações visando mitigar os impactos de rodovias sobre a fauna têm sido planejadas e implementadas ao redor do mundo (RYTWINSKI et al., 2016), sendo divididas em dois tipos: aquelas voltadas à mudança de comportamento dos usuários da rodovia, como redutores de velocidade, placas sinalizadoras e sistemas de detecção animal (HUIJSER et al., 2015); e aquelas voltadas ao manejo da fauna, como passagens subterrâneas (BHARDWAJ et al., 2017; CLEVENGER; WALTHO, 2005; JUMEAU; PETROD; HANDRICH, 2017; SMITH; VAN DER REE; ROSELL, 2015) e sobre a rodovia (GOOSEM; WESTON; BUSHNELL, 2005; SOANES et al., 2013; TEIXEIRA et al., 2013), cercas direcionadoras e refletores (BENTEN; ANNIGHÖFER; VOR, 2018; D'ANGELO; VAN DER REE, 2015; GLISTA; DEVAULT; DEWOODY, 2009). Contudo, o sucesso dessas ações depende diretamente da escolha das medidas mais adequadas a cada situação e da correta definição dos locais para sua implementação. Entretanto, definir esses locais não é uma tarefa fácil. Para diferentes contextos haverá diferentes formas que possibilitarão indicar os locais. Na minha tese de doutorado explorei diferentes abordagens para identificar esses lugares dependendo do tipo de dado disponível.

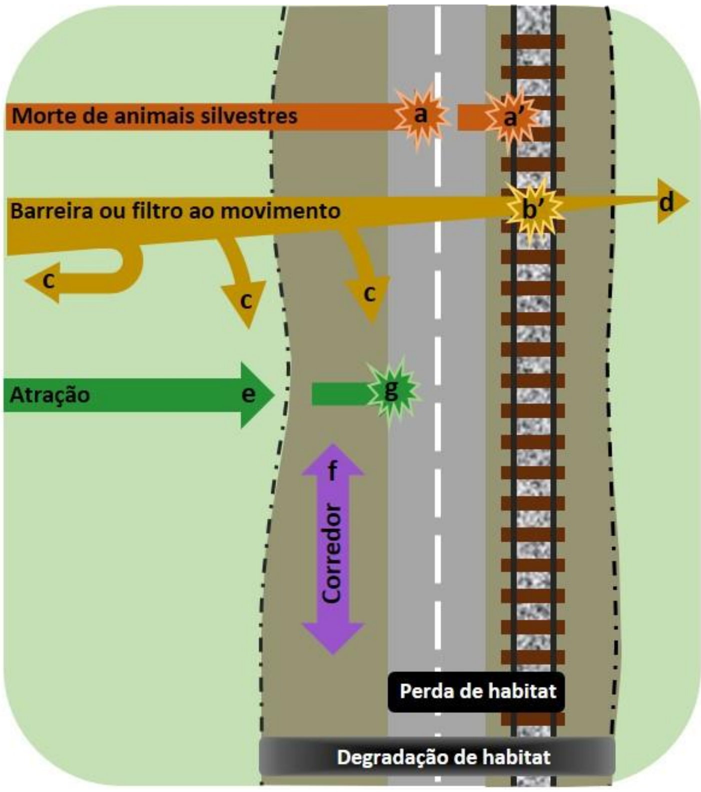


Figura 1. Impactos de rodovias e ferrovias na fauna silvestre, perda de habitat causada pela instalação das infraestruturas e degradação do habitat adjacente. Ao tentar cruzar, muitos animais podem morrer por colisões com veículos ou trens (a, a') ou ainda por ficarem presos entre os trilhos (b'). Já o efeito de barreira ou filtro ocorre porque a presença da rodovia e da ferrovia impede que os animais cruzem ou diminuem seu acesso para o outro lado (c) e alguns animais morrem ao tentar cruzar, fazendo com que apenas alguns indivíduos consigam atravessar com sucesso (d). A estrada e suas cercanias também podem ser um atrator (e) para a fauna e a vegetação adjacente ou a própria estrada podem atuar como corredor (f), tanto para espécies nativas como invasoras, eventualmente resultando em um mecanismo adicional de fatalidades (g). Figura retirada de TEIXEIRA et al. (2018) adaptada de VAN DER REE; SMITH; GRILO (2015).

Minha tese

Essa tese nasceu da vontade de pesquisar algo que fosse diretamente aplicado, que pudesse de alguma forma ajudar a orientar estratégias de mitigação dos atropelamentos de fauna em rodovias no Brasil e no mundo.

Se houver a possibilidade de monitorar uma estrada e obter dados de fauna atropelada, claramente eu posso usar essa informação para informar os locais onde foram encontrados mais animais atropelados. Dados de monitoramento sistemático (sejam eles semanais, quinzenais, mensais, trimestrais) podem ser usados para fazer uma análise de agregações de atropelamentos e identificar onde estão os locais em que essa concentração é maior do que o esperado ao acaso, identificando os *hotspots* de atropelamento. Esse foi o enfoque da primeira parte da minha tese (capítulo 1) que explorou padrões de mortalidade de répteis em uma estrada do sul do Brasil. Esse trabalho explorou dados de répteis atropelados em 33 meses de monitoramento mensais em 277 km da BR-101 e avaliou tanto o padrão espacial quanto o padrão temporal de fatalidades, além de estimar a magnitude de atropelamentos de répteis nessa estrada.

A abordagem explorada no capítulo 1 é extremamente útil no contexto de uma estrada construída e já operando, na qual é possível obter dados de atropelamento. Entretanto, o que fazer se eu preciso indicar locais para mitigação em estradas que estão sendo planejadas ou ainda se eu preciso indicar locais prioritários para mitigação em uma rede de estradas, onde o custo para realização de um monitoramento sistemático é altíssimo e as vezes temporalmente inviável. Será que eu consigo indicar locais com maior incidência de atropelamentos sem utilizar os dados de atropelamento para isso? Essa foi a pergunta motivadora dos próximos dois capítulos da tese.

No segundo capítulo, eu testei se usando características da paisagem, da rodovia e dos animais, eu posso predizer onde estão os locais com maior chance de um animal ser atropelado. Eu baseei minha ideia no modelo conceitual apresentado na figura 2. A ideia foi reconhecer os dois processos que acontecem sequencialmente para que um animal seja atropelado. Primeiro o animal precisa tentar cruzar uma estrada, depois ele precisa ser atingido por um veículo. Os lugares mais críticos para a ocorrência de fatalidades serão, assim, os locais de maior probabilidade de cruzamento de um animal e onde há maior probabilidade de um veículo colidir com ele. Modelos preditivos foram previamente propostos, mas raramente foram validados. Para calcular a probabilidade de colisão, HELS & BUCHWALD (2001) propuseram uma equação largamente utilizada (GRILO et al., 2018; JAARSMA et al., 2007; LITVAITIS; TASH, 2008), contudo desconhecemos trabalhos que tenham validado as predições. Da mesma forma, a probabilidade de cruzar a estrada tem sido avaliada por distintas abordagens (BASTILLE-ROUSSEAU et al., 2018; GIRARDET; FOLTÊTE; CLAUZEL, 2013; GRILO et al., 2011; KANG et al., 2016) e utilizada em modelos preditivos, mas raramente validada (PATRICK et al. 2012).

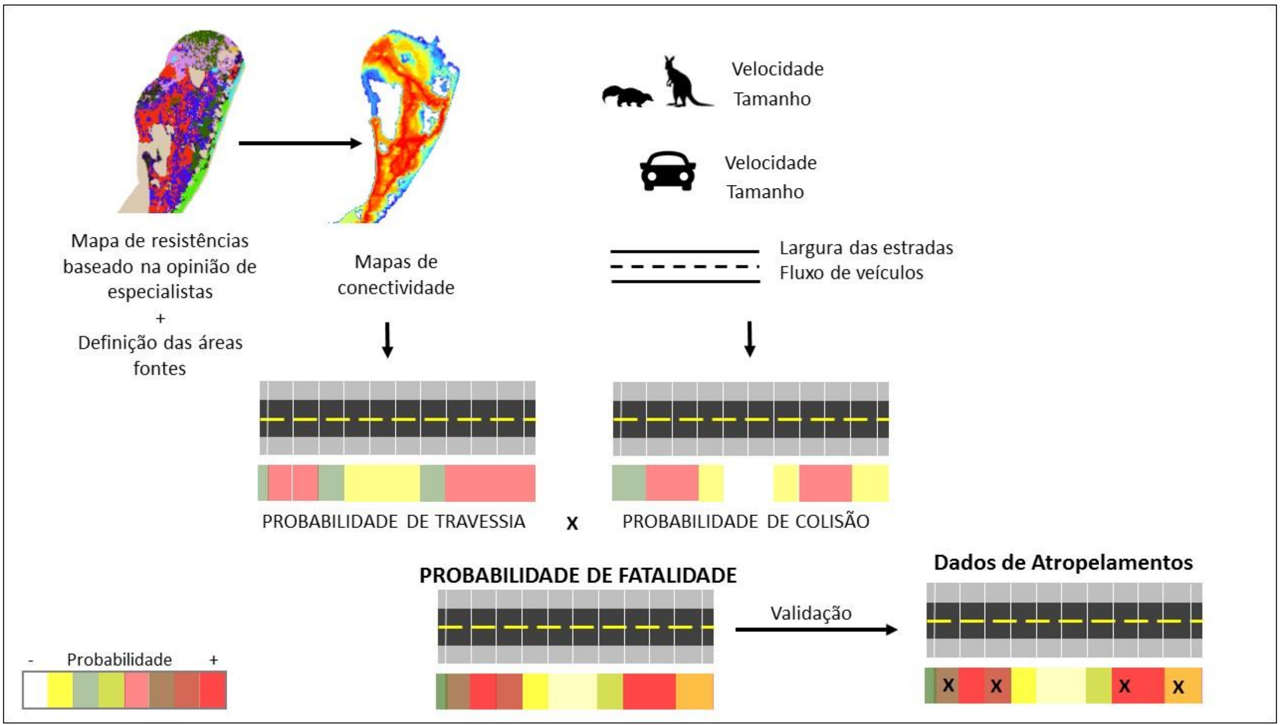


Figura 2. Esquema com as principais etapas e fatores necessários para o desenvolvimento do modelo de probabilidade de fatalidade que baseou o desenvolvimento dos capítulos 2 e 3 desta tese.

O segundo capítulo foi focado em uma única estrada. Eu usei o mesmo trecho da BR-101 usado no primeiro capítulo da tese e construí um modelo de probabilidade de fatalidades para duas espécies de mamíferos nativos: o furão (*Galictis cuja*) e o zorrilho (*Conepatus chinga*). A ideia foi explorar uma abordagem útil para ser usada em estradas a serem construídas ou pavimentadas; nessas últimas espera-se um elevado incremento de velocidade e tráfego de veículos e é bastante difícil obter observações de mortalidade em número suficiente para fazer uma avaliação como feita no primeiro capítulo. No contexto de uma estrada nova, é possível modelar o tráfego e a velocidade prevista para a futura estrada e já se conhece a paisagem do entorno sabendo o traçado proposto. Assim, seria possível construir os modelos antes da construção ou pavimentação de estradas e propor locais para implementação de mitigação. Eu construí uma série de mapas de conectividade que foram usados para extrair a probabilidade de travessia e usei o tráfego de veículos, o tamanho do carro, do animal, da estrada e a velocidade com que o animal atravessa a estrada para calcular a probabilidade de colisão de cada espécie na estrada. Além disso, eu multipliquei essas probabilidades para obter a probabilidade de fatalidade final. Mas como saber se esses trechos são mesmo os trechos com maior fatalidade e se essa probabilidade integrada final tem um maior poder preditivo do que as probabilidades individuais? Eu validei os modelos e avaliei a capacidade de predição de cada uma dessas probabilidades usando dados de atropelamentos de furão e zorrilho na mesma estrada, para os mesmos trechos, obtidos em um monitoramento sistemático de fauna atropelada.

A partir do segundo capítulo, surgiu a vontade de aplicar o mesmo modelo para uma rede de estradas. A primeira ideia era aplicar para estradas do Rio Grande do Sul, entretanto a dificuldade de acesso aos dados, principalmente de fluxo de veículos nos levou a pensar em alternativas. Ao longo desse percurso, me deparei com um artigo que propôs uma estrutura muito parecida com a minha (Visintin et al. 2016). O trabalho usava a mesma ideia de dois processos hierárquicos para que um animal fosse atropelado: a exposição à estrada e o perigo de atropelamento. A diferença é que neste trabalho, os autores utilizaram a ocorrência da espécie como a probabilidade de travessia e o fluxo e a velocidade dos veículos como a probabilidade de colisão. A partir da oportunidade do Doutorado Sanduíche pela CAPES, resolvi propor os modelos do segundo capítulo para os dados da rede de estradas do estado de Victoria na Austrália e avaliar o poder de predição dos modelos para um contexto de rede de estradas. Desenvolvi o terceiro capítulo em quatro meses na Austrália junto ao Grupo de Ecologia Quantitativa e Aplicada da Universidade de Melbourne.

No terceiro capítulo, utilizei dados da rede de estradas australianas no estado de Victoria (227.819 km^2), focando no canguru cinza oriental (*Macropus giganteus*) como espécie-alvo. A partir de mapas de uso e cobertura do solo e da ocorrência da espécie, eu construí mapas de conectividade que foram usados para extrair a probabilidade de travessia. A probabilidade de colisão considerou o fluxo de veículos, a velocidade da espécie e a largura das estradas, pois há dados dessa natureza disponíveis para toda a rede. Utilizei 47.730 trechos de 500 metros e obtive a probabilidade de travessia e a probabilidade de colisão para cada um dos trechos. A validação foi feita com dados de presença de atropelamento em cada trecho baseado em ocorrências reportadas para a Wildlife Victoria (WILDLIFE VICTORIA, 2015), organização que trabalha com bem-estar animal.

Além desta introdução geral, está tese está estruturada em três capítulos que correspondem a três artigos científicos e uma última seção de considerações finais. Nessa última, fiz um detalhamento das principais conclusões de cada um dos capítulos e de como essa tese pode contribuir para o estudo do impacto de atropelamento de fauna e da proposição de medidas de mitigação.

Capítulo 1

Atropelamento de répteis no sul do brasil: composição, hot moments e hotspots

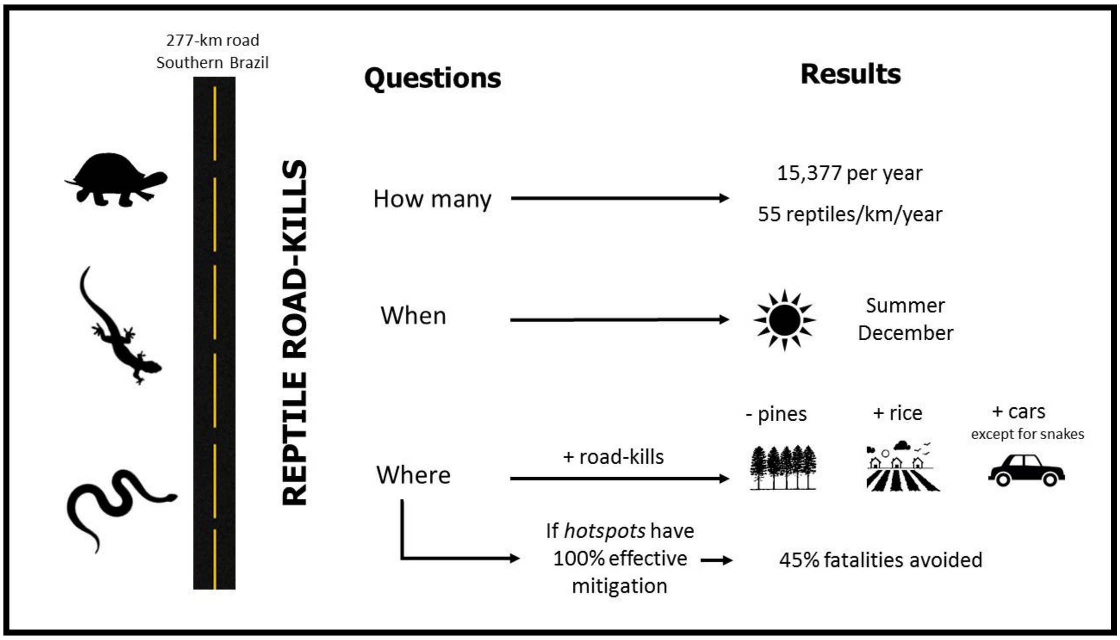
Esse capítulo está publicado na revista Science of the Total Environment e foi feito em colaboração com Diego Janisch Alvares, Fernanda Zimmermann Teixeira, Gabriela Schuck, Igor Pfeifer Coelho, Isadora Beraldi Esperandio, Juan Anza, Júlia Beduschi, Vinicius Augusto Galvão Bastazini. Ele pode ser acessado em https://doi.org/10.1016/j.scitotenv.2017.09.053.

Reptile road-kills in Southern Brazil: composition, hot moments and hotspots

HIGHLIGHTS

- Estimate of 15,377 freshwater turtles, lizards, and snakes road-killed per year;
- Road-kill hot moments in summer, especially in December for lizards and snakes;
- Road-kill hotspots highly coincident among freshwater turtles, lizards, and snakes;
- Positive effects of traffic and rice plantation, and negative of pine plantation;
- Hotspots (21% of the road extent) included 45% of reptile fatalities.

GRAPHICAL ABSTRACT



ABSTRACT

Understanding road-kill patterns is the first step to assess the potential effects of road mortality on wildlife populations, as well as to define the need for mitigation and support its planning. Reptiles are one of the vertebrate groups most affected by roads through vehicle collisions, both because they are intentionally killed by drivers, and due to their biological needs, such as thermoregulation, which make them more prone to collisions.

We conducted monthly road surveys (33 months), searching for carcasses of freshwater turtles, lizards, and snakes on a 277-km stretch of BR-101 road in Southernmost Brazil to estimate road-kill composition and magnitude and to describe the main periods and locations of road-kills. We modeled the distribution of road-kills in space according to land cover classes and local traffic volume. Considering the detection capacity of our method and carcass persistence probability, we estimated that 15,377 reptiles are road-killed per year (55 reptiles/km/year). Road-kills, especially lizards and snakes, were concentrated during summer, probably due to their higher activity in this period. Road-kill hotspots were coincident among freshwater turtles, lizards, and snakes. Road-kill distribution was negatively related to pine plantations, and positively related to rice plantations and traffic volume. A cost-benefit analysis highlighted that if mitigation measures were installed at road-kill hotspots, which correspond to 21% of the road, they could have avoided up to 45% of recorded reptile fatalities, assuming a 100% mitigation effectiveness. Given the congruent patterns found for all three taxa, the same mitigation measures could be used to minimize the impacts of collision on local herpetofauna.

Keywords: carcass detection, carcass removal, mitigation, road ecology, road-kill aggregation, wildlife-vehicle collisions

1. Introduction

Among several road impacts on wildlife, such as habitat loss, degradation, and fragmentation, fatalities due to vehicle collisions are one of the most concerning impacts (Forman et al., 2003; van der Ree et al., 2015b). Road mortality can cause faster population declines compared to other impacts, such as connectivity reduction (Jackson and Fahrig, 2011; Jaeger and Fahrig, 2004). Road-killing can also foster evolutive changes in populations (Brady and Richardson, 2017). Understanding patterns and processes related to wildlife-vehicle collisions is fundamental for guiding policies to minimize their impact.

Despite the long interest in understanding the effects of reptile-vehicle collisions (Fitch, 1949) and the fact that this group seems to be more affected than other vertebrates (D'Amico et al., 2015; Jochimsen et al., 2014), reptiles are still underrepresented in road ecology literature (Fahrig and Rytwinski, 2009; Gunson et al., 2011). The lesser interest on reptile fatalities is probably explained by the importance that other vertebrate groups, such as medium and large mammals, pose to human safety (Danks and Porter, 2010; Huijser et al., 2009). However, when mitigations are planned aiming to reduce the anthropogenic impact on biodiversity, relying on information available for a single taxonomic group might be ineffective, since road-kill patterns in space (e.g. Teixeira et al., 2013b) and time can vary among distinct taxonomic or functional groups.

Even without knowledge of the demography of local populations, understanding which species and how many animals die on roads can be the first step to assess the potential effects of road mortality on wildlife populations, as well as to define the need for mitigation and support its planning. Road-kill estimates need to incorporate inherent errors of carcass surveys, such as imperfect detection and carcass persistence (Santos et al., 2011; Teixeira et al., 2013a). Studies accounting for these errors on reptile road-kill estimates are rare (but see Gerow et al., 2010 and Teixeira et al., 2013a) and the real magnitude of reptile mortality is certainly underestimated. Road mortality effects are not equally distributed in time and space (Beaudry et al., 2010), therefore assessing road-kill hot moments and hotspots, i.e. periods and locations with significantly higher fatalities, is important to propose periods and locations for mitigation (Gunson and Teixeira, 2015).

Both intrinsic and extrinsic factors can affect road-kill distribution. Species have life traits that make them more vulnerable to vehicle collisions, such as mobility and behavioral responses to traffic volume (Jacobson et al., 2016; Lima et al., 2014). Landscape and road characteristics certainly affect road-kill patterns. Variables related to the presence and distance of water bodies and to traffic volume are recognized as important factors determining spatial patterns of reptile fatalities on roads (Glista et al., 2008; Langen et al., 2012, 2009).

Knowledge of environmental or road attributes related to higher road-kill probability can be used to identify priority periods and locations for mitigation on other roads, for which road-kill data are unavailable (D'Amico et al., 2015; Glista et al., 2008). Although there is a number of possible mitigation strategies potentially beneficial for reptiles, passages associated with funneling fencing seem to be the most effective for multispecies purposes (Jackson et al., 2015). Currently available technologies allow for implementation of mitigation structures during road operation with relatively little trouble to traffic, whereas proper design, implementation and maintenance could result on nearly absolute effectiveness (Aresco, 2005; Van der Ree and Tonjes, 2015).

In this study, we described road-kill patterns for freshwater turtles, lizards, and snakes on BR-101 road, Southernmost Brazil. We evaluated which species are road-killed, how many reptiles are killed on this road (considering carcass removal and detection based on experiments), and when and where these road-kills are concentrated. We also assessed the relationship of reptile fatalities with land cover and local traffic volume. We expected temporal patterns to show a concentration of fatalities in summer months due to higher reptile activity in this period. We expected distinct spatial distribution of fatalities for each group, considering they vary in natural history: freshwater turtles are more associated with aquatic environments, while lizards tend to occupy open and forested areas. For snakes, we expected the spatial pattern of fatalities to be less aggregated due to their higher regional species richness. We also expected that traffic volume would have a stronger association with freshwater turtle fatalities than with other groups because they are less mobile and present a 'pauser' behavior in reaction to upcoming vehicles (Jacobson et al., 2016).

2. Methods

2.1. Study area

We conducted this study on a 277-km stretch of BR-101 road, located at the lowlands of Rio Grande do Sul state, Brazil (initial coordinates 30°9'1.20"S and 50°30'49.33"W, and final coordinates 32°0'23.64"S and 52°2'17.73"W; see Fig.2; Appendix A). BR-101 is located in the eastern side of Patos Lagoon, adjacent to the Lagoa do Peixe National Park, a recognized Ramsar site (Ramsar Convention, 1962).This stretch is a two-lane paved road with 11 m of width, a speed limit of 80 km/h, and an average daily traffic (ADT) between 690 and 2,900 vehicles, depending on the locality.

2.2. Data Collection

We conducted monthly surveys from September 2012 to August 2014, and from February to October in 2015, totaling 33 surveys. Two observers (including the driver) conducted surveys by car at 40-50 km/h (speed limit followed minimum allowed speed according to Brazilian regulation) from dawn to dusk. Detected carcasses were identified to the lowest taxonomic level and their locations were georeferenced with a handheld GPS.

We used vehicle counters (Vehicle Counter Generation III - TRAFx Research Ltd.) to calculate the average daily traffic (ADT) in three locations linking the main regional settlements: Capivari do Sul (n=48 days), Mostardas (n=273 days), and São José do Norte (n=498 days). Since we found a north-to-south decrease in traffic volume, we extrapolated traffic volume for each 2-km road segment by performing a linear regression with the recorded ADT in each surveyed location and the distance to the northernmost city (Capivari do Sul).

We used a land cover map from LANDSAT 5 TM images classification for 2009 (UFRGS-IB-Centro de Ecologia, 2016) with eight classes: wetlands, native forest, dry grassland, water, pine plantation, rice plantation, urban areas and mixed areas (various crops, annual or perennial, and degraded grasslands). We calculated the area of each of the eight land cover classes within a 2-km buffer centered on each 2-km road segment.

2.3. Data Analyses

We assumed that collision risk is related to movement capacity, and grouped reptile species according to their behavioral responses to traffic volume for subsequent analyses (Jacobson et al., 2016). Freshwater turtles usually freeze on the road in response to vehicle presence (‘pausers’), lizards usually flee (‘speeders’) and snakes usually do not respond to vehicles (‘non-responders’) or show responses as ‘pausers’ or ‘speeders’ (Jacobson et al., 2016). Therefore, we analyzed freshwater turtles, lizards, and snakes (we included amphisbaenians in snakes group) as separate groups.

2.3.1. Estimates of road-kill magnitude

We estimated road-kill magnitude for all reptiles, freshwater turtles, lizards, and snakes through *Nestimate* function based on Korner-Nievergelt et al. (2011) using the *Carcass* package (Korner-Nievergelt et al., 2015) in R environment (R Core Team, 2016). This estimate considers the detection capacity of the method, carcass persistence on the road, number of surveys and survey interval. This method assumes that search intervals are regular and persistence probability and search efficiency are constant over time. Carcass persistence was estimated based on the exponential model (Korner-Nievergelt et al., 2011).

To assess carcass detection and persistence we performed experiments by placing 56 carcasses of reptiles (five freshwater turtles and 51 snakes) previously collected on BR-101 road on a 30-km stretch of the same road. Detection was evaluated for six survey teams (each of them with two observers following the same method used in regular surveys) who monitored this 30-km stretch without knowing the location of carcasses. After all teams had surveyed the road, we checked every carcass placed and found that ten had been removed. Therefore, we considered 46 carcasses (four freshwater turtles and 42 snakes) for evaluating the probability of detection of the method: 14 carcasses smaller than 15 cm, 27 from 15 to 35 cm, and five larger than 35 cm. To estimate carcass persistence, we used the total 56 carcasses, checking their persistence for five consecutive days. We used *search.efficiency* and *persistence.prob* functions from the *Carcass* package to calculate carcass detection and persistence separately for freshwater turtles and snakes. As we did not include lizard carcasses in our experiment, we used detection and persistence values from snake carcasses. We used carcass detection and persistence calculated considering all carcasses as values for reptiles.

2.3.2. *Road-kill hot moments*

We analyzed road-kill hot moments for freshwater turtles, lizards, and snakes using circular statistics in Oriana 4.02 software (Kovach, 2004) considering only data collected during the first two continuous years of surveys. Months were converted in angles (30-degree intervals) and the sum of road-kills in each month was used as a frequency for each angle. We then obtained the mean angle, which represents the average period with the highest number of fatalities within the whole period. We assessed the significance of the average period in relation to an uniform distribution of road-kills through the Rayleigh test of uniformity, Z (Kovach, 2004). Then, we calculated the intensity of road-kill concentration through the average period length (r), which varies from 0 (uniform dispersion) to 1 (road-kill concentration in the same direction).

2.3.3. Road-kill hotspots

We evaluated on which scales road-kill hotspots occurred for freshwater turtles, lizards, and snakes using Ripley's K statistic (Levine, 2000; Ripley, 1981) at a bidimensional space in Siriema v.2.0 software (Coelho et al., 2014). We used an initial radius of 300 m, a radius increase of 500 m, and 100 simulations of random distribution events to evaluate clustering significance (99% confidence interval). After the identification of the scales with road-kill hotspots, we performed a 2D HotSpot Identification analysis for recognizing where hotspots were located. We used a 1-km radius and divided the road into 138 segments of 2 km each. We chose this segment length because Ripley's K statistic identified the occurrence of clustering on that scale and because some mitigation measures for reptiles can be easily implemented targeting a 2-km road segment, as for example, a wildlife passage connected by funnel fencing (Baxter-Gilbert et al., 2015). We performed 1,000 simulations of random distribution to assess significance of hotspots locations (95% confidence interval). We considered as hotspots all segments with a road-kill intensity value higher than the upper confidence limit (Coelho et al., 2014).

As many hotspots might be identified on a road and, in most cases, there are budget restrictions to mitigating all of them, we evaluated the relative contribution of mitigating hotspots. We calculated the potential reduction in road-kills in the case of mitigating each of the road segments identified as hotspots for at least one of the three reptile groups studied. We sorted hotspots by their intensity and we built a cumulative curve of the number of road-kills recorded at each hotspot location as a proxy of the potential gain obtained by mitigation.

2.3.4. Road-kill association with land cover and traffic volume

To assess the relationship of road-kills of freshwater turtles, lizards and snakes with land cover classes and traffic volume, we fit generalized linear models with a Poisson distribution. We divided the road into 2-km segments, using the same segments from the 2D HotSpot Identification analyses, and the number of road-kills in each segment was used as response variable. Predictive variables were standardized to have a mean of 0 and standard deviation equal to 1.

We used hierarchical partitioning (Mac Nally, 2002) to assess the influence of each predictive variable on the number of road-killed freshwater turtles, lizards, and snakes. Hierarchical partitioning uses models with all combinations of predictive variables to evaluate the independent (I) and joint (J) effect of each of them on the response variable. We tested the statistical significance of the contributions of independent variables using a randomization process (999 randomizations) based on a 95% upper confidence limit (Z-score>1,96). This statistical analysis was conducted in R (R Core Team, 2016) with the *hier.part* package using log-likelihood as the goodness-of-fit measure (Walsh and Mac

Nally, 2013). Then, we assessed the explained deviance of each full model (for freshwater turtles, lizards, and snakes) calculated as 1 - (residual deviance / total deviance).

3. RESULTS

3.1.1. Estimates of road-kill magnitude

We recorded 1,353 carcasses of reptiles on BR-101 road, 18% of which were freshwater turtles belonging to four species, 11% were lizards (Argentine Black and White Tegus, *Salvator merianae*), and 70% were snakes belonging to 24 species and one amphisbaenian species (*Amphisbaena trachura*) (Table 1; Appendix B). We estimated carcass detection as 55% (95% IC [26%, 82%]) for freshwater turtles and 23% (95% IC [15%, 34%]) for snakes and lizards. Carcass persistence probability for freshwater turtles was 0.85 in one day (95% IC [59%, 94%]) with a mean persistence time of six days. Carcass persistence probability for snakes was 0.82 in one day (95% IC [76%, 87%]) with a mean persistence time of 5.2 days. After correcting for carcass detection and removal, we estimated a total of 42,287 road-killed reptiles during 33 months of survey (Table 1), which corresponds to 15,377 road-killed reptiles per year (789 freshwater turtles, 1,600 lizards, and 10,206 snakes).

Table 1. Number of observed carcasses and estimates of road-kill magnitude for freshwater turtles, lizards, and snakes during 33 months of surveys on BR-101 road. Lower and upper 95% confidence limits are in parentheses.

Groups	Observed carcasses	Estimates of road-kill magnitude	Estimates of magnitude per year	Estimates of magnitude per km per year
Freshwater turtles	245	2,170 (550 - 9,206)	789 (200 - 3,347)	2.8 (0.7 - 12.1)
Lizards	151	4,400 (2,545 - 7,671)	1,600 (925 - 2,768)	5.8 (3.3 - 10.8)

Groups	Observed carcasses	Estimates of road-kill magnitude	Estimates of magnitude per year	Estimates of magnitude per km per year
Snakes	957	28,069 (16,654 - 48,631)	10,206 (6,056 - 17,684)	36.9 (21.8 - 63.8)
TOTAL	**1,353**	**42,287 (24,080 - 73,890)**	**15,377 (8,756 - 26,869)**	**55.55 (31.6 - 97.1)**

3.2. Road-kill hot moments

Fatalities of freshwater turtles were concentrated in January, while fatalities of lizards and snakes were significantly concentrated in December (Fig.1). Freshwater turtles were the group with the lowest road-kill concentration in time (r= 0.28; Z=9.7; p<0.001), followed by snakes with intermediate concentration values (r=0.47; Z=176.7; p<0.001), and lizards with the highest values (r = 0.80; Z = 88.2; p< 0.001).

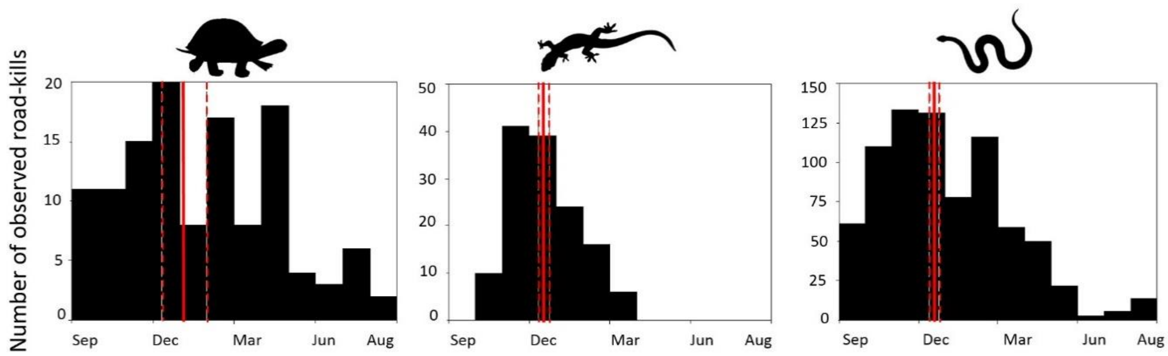


Fig. 1. Road-kill hot moments for freshwater turtles, lizards, and snakes during two years of surveys (September 2012 to August 2014). Mean concentration period (full red lines) and standard error (dashed red lines).

3.3. Road-kill hotspots

We found road-kill clustering from 300-m to 70-km scales for freshwater turtles, from 300-m to 162-km scales for lizards, and from 300-m to 78-km scales for snakes (Appendix C). 2D HotSpot Identification analyses indicated that most hotspots were concentrated in the Northern portion of the road, the segment with the highest traffic volume (Fig.2). For snakes, we also identified some hotspots also in the Southern part of the road (Fig.2).

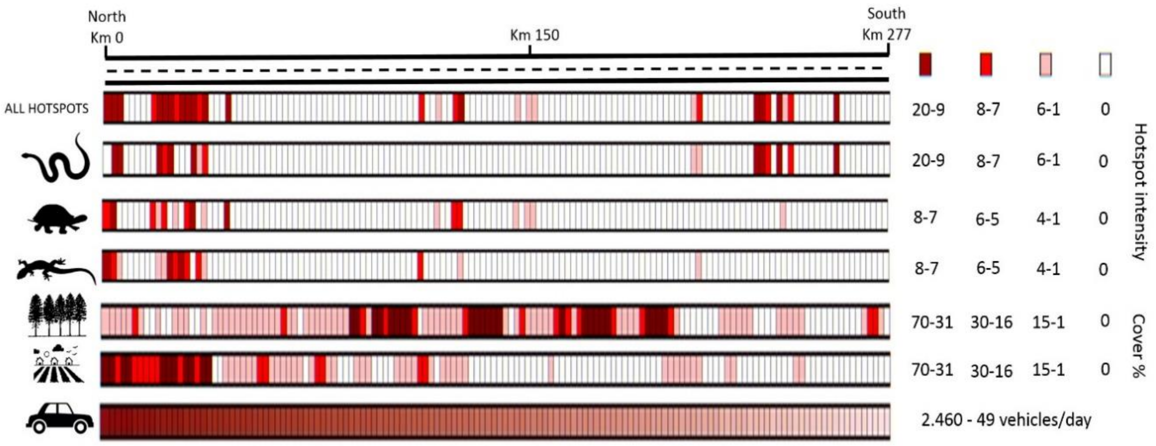


Fig. 2. Spatial distribution of hotspots (all reptile hotspots; snakes, freshwater turtles, and lizards hotspots separately), percentage of pine plantations, rice plantations, and traffic volume (ADT) along BR-101 road. Hotspot values correspond to road-kill intensity values from 2D Hotspot Identification analyses. Each segment corresponds to the 2-km road stretch used as sampling unit in the models.

When assessing road segments that were identified as hotspots for at least one of the groups, and assuming the proposed mitigation would be 100% effective, we can infer that 45% of reptile deaths could be avoided if 21.7% of the segments of the road (the 30 hotspot segments) had been mitigated (Fig. 3). That means a twofold efficiency in a cost-benefit relationship (km mitigated/road-kills avoided). If we detail this potential reduction by group, we would reach a 40% road-kill decrease for snakes, 53% for freshwater turtles and 60% for lizards (Fig. 3), a 2-3 cost-benefit rate.

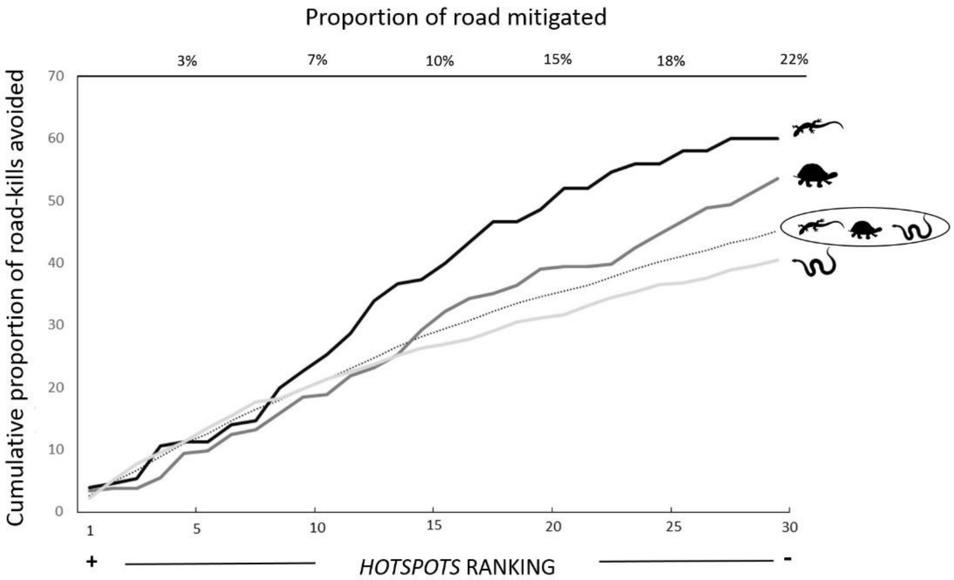


Fig. 3. Cumulative proportion of road-kills avoided for lizards, freshwater turtles, reptiles, and snakes considering the implementation of 100% effective mitigation measures on hotspots locations. Hotspots illustrated correspond to 21.7% of the road (upper x axis). Hotspots were ranked in the lower x axis in decreasing order of aggregation intensity.

3.4. Road-kill association with land cover and traffic volume

The amount of pine and rice plantations were the most important variables for determining the fatalities of freshwater turtles, lizards, and snakes (Table 2). Road-kills of freshwater turtles showed a significant positive relationship with rice plantations (I% = 26.23), urban areas (I% = 11.77), and traffic volume (I% = 8.68), and a significant negative relationship with pine plantations (I% = 34.07) and dry grasslands (I% = 8.95). For lizards, we found a positive relationship with rice plantations (I% = 33.06) and traffic volume (I% = 20.71), and a negative relationship with pine plantations (I% = 22.74). Snake fatalities were positively related to rice plantations (I% = 22.7) and mixed areas (I% = 8.59), and negatively related to rice plantations (I% = 45,75) and traffic volume (I% = 8.59).

Table 2. Results of variables' associations from the hierarchical partition for each group. 'Dev' is the percentage of explained deviance for models including all variables in each reptile group. The sign of each variable is obtained from a Poisson regression model and shows the relationship between each predictive variable and the response variable. 'I' and 'J' are respectively the independent and joint contribution of each variable for each reptile group. 'Total' is the sum of 'I' and 'J'. '%I' is the relative percentage of independent contribution for each variable. 'Z score' is the randomization test of the independent contributions for each predictive variable (* identifies significant variables).

	Freshwater turtles						Lizards						Snakes					
	Dev 39%	I	J	Total	%I	Z.score	Dev 44%	I	J	Total	%I	Z.score	Dev 44%	I	J	Total	%I	Z.score
Traffic volume	+	5.7	7.35	13.1	8.68	2.38*	+	12.9	20.1	33	20.7	6.6*	-	9.84	-8.16	1.68	8.95	3.14*
Water	+	0.33	-0.31	0.02	0.5	-0.53	-	1	0.62	1.62	1.61	-0.16	-	5.03	2.18	7.21	4.58	1.19
Urban area	+	7.73	5.09	12.8	11.8	3.84*	+	4.07	3.58	7.65	6.53	1.5	-	1.41	-1.13	0.28	1.28	-0.16
Wetland	-	0.52	-0.45	0.07	0.78	-0.46	-	1.82	3.44	5.26	2.92	0.33	+	1.86	0.75	2.61	1.69	-0.04
Native forest	+	2.52	-2.47	0.04	3.83	0.71	-	2.21	4.89	7.1	3.54	0.48	+	4.57	2.39	6.96	4.16	1.04
Dry grassland	-	5.88	2.14	8.01	8.95	2.49*	-	2.59	3.78	6.37	4.16	0.79	+	2.54	0.54	3.08	2.31	0.23
Mixed area	+	3.41	-2.38	1.03	5.2	1.28	+	2.95	-2.12	0.82	4.73	0.92	+	9.44	-2.36	7.08	8.59	2.94*
Rice plantation	+	17.2	14.6	31.8	26.2	8.58*	+	20.6	23	43.6	33.1	11.47*	+	25	-6.09	18.9	22.7	9.01*
Pine plantation	-	22.4	10.5	32.9	34.1	11.95*	-	14.2	8.54	22.7	22.7	8.28*	-	50.3	27.2	77.5	45.8	21.12*

4. DISCUSSION

We estimated that 55.55 reptiles are road-killed per kilometer per year (range: 31 - 97 reptiles/km/year), totaling more than 15 thousand road-killed animals every year on a 277-km segment of BR-101 road. The estimated road mortality magnitude obtained in this study corresponds to 30 times the number of observed carcasses during the road surveys, and exceeded the estimates of reptile road-kills on other roads, which did not consider carcasses detection and removal (e.g. de Souza et al., 2015; Hartmann et al., 2011; Pragatheesh and Rajvanshi, 2013). In a study conducted in the Brazilian Pantanal, 58 vertebrate road-kills were recorded per kilometer per year (de Souza et al., 2015), in which mammals were the most representative group (61%) and reptiles corresponded only to 13% of the total. This low reptile representation was also present in other studies (e.g. Bager and Fontoura, 2013). However, it is important to point out that both the relative frequencies and the road-kill rates are underestimated, since carcass detectability is associated with body size (Teixeira et al., 2013a) and lower for reptiles when compared to mammals.

A high proportion of the reptile species known for the region is potentially affected by road-kill. We recorded 72% of the known reptile species pool from the entire coastal lowlands of Rio Grande do Sul (Borges-Martins et al., 2007) and other seven species that were not in their inventory (two freshwater turtles and five snakes). The higher number of snake species recorded as road-kill is in agreement with its higher richness for the region.

The occurrence of a large number of reptile road-kills depends on two factors: (1) availability (higher exposure) and (2) lethality (higher risk of running over). In the case of reptiles, higher exposure to roads may be explained by: higher abundance near roads, necrophagy, and the habit of thermoregulation. The abundance of individuals in habitats along road verges is the most important factor determining availability, but it is rarely estimated to allow comparison (Meek, 2015, 2009). Still, several species of lizards and snakes are active foragers that prefer open environments, increasing the chance of using roads or open vegetation adjacent to roads for foraging (Brehme et al., 2013; Meek, 2009) and turtle females may use road edges for nesting (Aresco, 2004; Dorland et al., 2014). Necrophagy is part of the dietary habit of the only species of lizard recorded (11% of all records) in our study (Kiefer and Sazima, 2002; Sazima and D'Angelo, 2013), and it has been documented for our most recorded snake species (*Philodryas patagoniensis)* as well (Ucha and Santos, 2017). When animals are attracted to roads to feed on road-kills, they expose themselves to the risk of collisions with vehicles. In addition, reptiles might increase their exposure when they thermoregulate, as it has been demonstrated that the asphalt temperature is strongly related to the presence of snakes from different species on roads (Mccardle and Fontenot, 2016).

The second factor determining higher road-kill rates is lethality, which is related to traffic volume and, for the same traffic volume, to drivers' and animals' behaviors, as well as animal size and mobility. Road-kill rates are usually related to high or medium traffic volumes (Gunson et al., 2011), especially for species that do not avoid roads. Several studies demonstrated that drivers' intentional collision with snakes and turtles is higher than observed for control objects (Ashley et al., 2007; Beckmann and Shine, 2012; Langley et al., 1989; Secco et al., 2014), and higher for snakes than for freshwater turtles (Ashley et al., 2007). Crawford & Andrews (2016) demonstrated that drivers would be less upset (a proxy of intention or care by the authors' point of view) when they run over a snake than when they run over a turtle or a large mammal. Considering animal size, Whitaker & Shine (2000) suggested that snakes are a larger target for vehicle collisions because their body is longer in relation to other animals' when they cross the road perpendicularly. In relation to animal mobility, Andrews & Gibbons (2005) pointed out that some snakes and turtles have an immobilization behavior in response to vehicle approximation ('pausers' category in Jacobson et al., 2016) and could be an additional explanation for their higher road-kill rate together with their lower crossing speed.

Road-kill hot moments were concentrated mostly in summer months. This temporal pattern has been demonstrated in other studies for reptiles as a whole (Garriga et al., 2017), for freshwater turtles (Cureton II and Deaton, 2012), and for lizards (Meek, 2014). Hot moments have been shown to be related to climate variables, such as temperature and precipitation (Garriga et al., 2017), which influence the breeding season (Cureton II and Deaton, 2012), foraging (Meek, 2014), and species movement (Andrews and Gibbons, 2005; Shine et al., 2004). Lizard from the only species recorded in our study (*Salvator* *merianae*) are inactive almost half of the year (Borges-Martins et al., 2007), with the active period in the warm months, when they move to reproduce and to forage, increasing the probability of using roads. Temporal patterns of fatalities could differ among species (Mccardle and Fontenot, 2016; Meek, 2014), as well as among sex and age classes (Jochimsen et al., 2014), thus temporal patterns could be still more restrictive than observed because it is related to specific behavior characteristics, as thermal biology (Mccardle and Fontenot, 2016).

Road-kill hot moments can be used to plan the implementation of temporary structures such as directional fences, associated with specific wildlife underpasses for reptiles (Baxter-Gilbert et al., 2015; Markle et al., 2017). The implementation of temporal directional fences can be interesting due to their lower costs, even considering the costs of installation and maintenance. Whenever reptiles are the target group for mitigation, the existence of road-kill hot moments allows the concentration of field efforts to evaluate and monitor reptile road-kills during the period with higher fatality frequency. This would abbreviate decision-making and reduce associated costs.

Road-kill hotspots were predominantly coincident between freshwater turtles, lizards, and snakes, except for some aggregations of snake road-kills that were located in the southern portion of the road. The coincidence among hotspots for different groups allows mitigation strategies to be designed for the reptile group as a whole, always considering that mitigation measures must be effective in their implementation and operation, since small installation or maintenance failures can have great consequences on their effectiveness (Baxter-Gilbert et al., 2015). We hereby demonstrated that if effective mitigation measures were installed on top ranking hotspots, which represent a relatively small proportion of the road (21%), they could contribute to reduce observed fatalities in 45%. This twofold cost-benefit ratio was obtained assuming an absolute effectiveness of mitigation that could be attained with well-planned passages associated to drift fences with recurrent maintenance (Jackson et al., 2015; Van der Ree and Tonjes, 2015).

Under some circumstances, such as older roads, the use of hotspots for defining mitigation locations may not be the most adequate measure, as hotspots can change over time (as from high-traffic segments to low-traffic segments), as a consequence of population depletion by road mortality (Teixeira et al., 2017). However, this may not be the case for the road segment studied here, as its paving started in 1993 for the first 120 km (near Mostardas city) and finished in 2009 for the entire 277-km segment (near São José do Norte city). Furthermore, we observed a positive relationship between fatalities and traffic volume (which decreases from north to south), except for snakes, the group with hotspots both at the northern and at the southern portions of the road.

The proportion of pine plantations was the most important land cover variable that influenced fatalities of freshwater turtles, lizards, and snakes, with a relatively strong negative effect. This negative relationship has already been highlighted for other wildlife groups, such as owls (Gomes et al., 2009). Moreover, the impoverishment of habitat and wildlife caused by exotic pine and/or eucalyptus plantations has been extensively documented, especially in grassland dominated landscapes (Berthrong et al., 2009; Brockerhoff et al., 2008; Corley et al., 2006). Even in forest environments, such as in the northeastern Brazilian Amazon, the richness of both amphibians and lizards was lower in eucalyptus plantations than in native primary and secondary forests (Gardner et al., 2007; Saccol et al., 2017). The presence of pine plantations is probably reducing the abundance and richness of reptiles in the areas surrounding the road, decreasing their availability to be road-killed.

Rice plantations coverage was already recognized as determinant for reptile hotspots (Grilo et al., 2016; Seo et al., 2015), as these human-modified environments provide refuge for some wetland species. Water bodies or wetlands at road margins are recognized as important features for determining road-kill aggregations, both for vertebrates in general (Freitas and Federal, 2015) and for freshwater turtles (Cureton II and Deaton, 2012; Langen et al., 2012). However, we did not find a relationship between the percentage of water cover and fatalities, probably because the water category considered in our mapping represents only large water bodies (lakes and lagoons) and what probably matters to these animals are the wet areas close to the road, such as puddles and ditches. Not only the cover percentage, but also the distance to water bodies is important for turtles and can show a negative relationship with the presence of freshwater turtles hotspots (Langen et al., 2012). As expected, we found a negative relationship between dry grassland percentage and freshwater turtle fatalities.

For vertebrates in general (Seo et al., 2015), and especially for reptiles, traffic volume is widely recognized as responsible for fatality locations (see Cureton II & Deaton, 2012, and Langen et al., 2012 for freshwater turtles). Contrary to this pattern, we found a negative relationship between traffic volume and road-kill density for snakes. Some snakes may be avoiding to cross the road in areas where traffic volume is high (Siers et al., 2016) or some snake populations have already suffered a decline in these areas and have lower abundance, decreasing their interaction with the road (Teixeira et al., 2017). In addition, habitat quality in areas with lower traffic may be better (Shepard et al., 2008), allowing larger populations to thrive.

Regardless of the explanations for the occurrence of road-kills (single or multiple causes or even their interactions), road mortality for the different groups evaluated showed congruent spatial and temporal patterns. Considering this scenario, the best strategy for an effective multispecific mitigation is to diminish the interaction between animals and the road or traffic, providing opportunities for safe crossings at each hotspot segment, associating multiple wildlife passages with directional fences specific for reptiles (Andrews et al., 2015; Jacobson et al., 2016; Markle et al., 2017). To reduce deterioration or even theft of fences, they could be installed temporarily only during summer months, although the cost-benefit of recurrent installation needs to be evaluated in comparison to permanent fences. Absolute exclusion of animals from the road should be followed by frequent maintenance inspections. Also, sufficient jump-out opportunities for animals that get stuck between fences should be provided as a complementary measure (van der Ree et al., 2015a). By adopting this set of relatively low-cost measures, we expect a significant reduction of the present-day carnage observed on this road.

5. CONCLUSION

Reptile fatalities in the Southern portion of BR-101 road were temporally and spatially aggregated, with hotspots and hot moments overlapping among different reptile groups. The high number of fatalities may be associated with the recent paving of this road (ended in 2009), which influenced traffic volume and vehicle speed. Since then, traffic volume has been rising and is predicted to further increase following higher human occupation in the region. When sorting hotspots by intensity of road-kill hotspots, we demonstrated a cost-benefit rate of mitigation (km mitigated/road-kills avoided) of 1:2 for reptiles and even larger for single groups. By showing that areas of pine and rice plantations and that traffic volume were important for explaining reptile road-kills, we provided some clues for mitigation planning on roads in similar landscapes where road-kill data is not available, and indicated important variables for the development of predictive models.

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APPENDIX A.

KML file with road track, hotspots intensity of freshwater turtles, lizards and snakes.

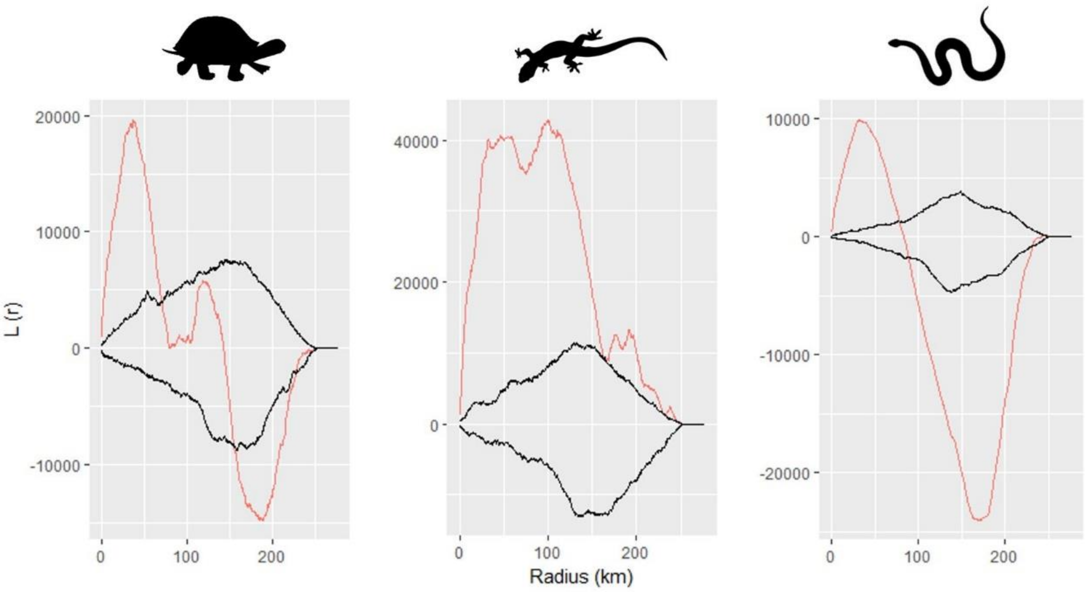
APPENDIX B.

Species list (Scientific and common names) and number of observed carcasses during 33 months of monitoring in the road BR-101.

Cientific Name	Common Name	Observed carcass
Freshwater Turtles		**245**
Trachemys dorbigni	Black-bellied Slider	130
Acanthochelys spixii	Black Spine-necked Swamp Turtle	72
Phrynops hilarii	Hilaire’s Side-necked Turtle	32
Hydromedusa tectifera	South-American Snake-headed Turtle	1
Unidentfied freshwater turtles	-	10
Lizards		**-**
Salvator merianae	Argentine Black and White Tegu	151
Snakes and Amphisbaenians		**957**
Philodryas patagoniensis	Patagonia Green Racer	163
Erythrolamprus poecilogyrus	Yellow-bellied snake	147
Helicops infrataeniatus	Water snake	141
Erythrolamprus semiaureus	Water snake	114
Thamnodynastes hypoconia	-	59
Erythrolamprus jaegeri	Jaeger's Ground Snake	48
Xenodon dorbignyi	South American Hognose Snake	37
Boiruna maculata	Mussurana	34

Cientific Name	Common Name	Observed carcass
Oxyrhopus rhombifer	Amazon False Coral Snake	31
Philodryas aestiva	Brazilian Green Racer	31
Xenodon merremii	Wagler's Snake	30
Lygophis anomalus	-	22
Bothrops alternatus	Urutu	13
Mastigodryas bifossatus	Rio Tropical Racer	12
Philodryas olfersii	Lichtenstein's Green Racer	9
Bothrops pubescens	Pampa's lancehead snake	7
Lygophis flavifrenatus	Fronted Ground Snake	5
Erythrolamprus almadensis	Almaden Ground Snake	4
Sibynomorphus neuwiedi	Neuwied's Tree Snake	4
Atractus reticulatus	Reticulate Ground Snake	2
Phalotris lemniscatus	Dumeril's Diadem Snake	3
Chironius bicarinatus	Two-headed Sipo	1
Psomophis obtusus	Wide Ground Snake	1
Taeniophallus poecilopogon	-	1
Erythrolamprus sp.	-	1
Unidentfied snakes	-	24
Amphisbaena sp.	Blinded-snake	10
Amphisbaena trachura	Blinded-snake	2
Unidentfied reptile	-	1
TOTAL		**1.353**

APPENDIX C.



FigS1: L statistic (K observed − K simulated mean; red lines) as a function of scale distance (radius) and 99% confidence limits (black lines) for the spatial distribution of road-kills of freshwater turtles, lizards and snakes on BR-101.

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Capítulo 2

As probabilidades de travessia e colisão predizem as fatalidades de fauna em rodovias?

Este capítulo será submetido como research paper para a revista Conservation Biology e está formatado conforme as normas da revista. Ele foi feito em colaboração com Bruna Arbo Meneses e Casey Visintin.

Do crossing and collision probabilities predict wildlife fatalities on roads?

Abstract

Predicting road-kills is one of the most urgent task in a context of new roads and road expansion, when there are no road-kill data. We aimed to test if the integration of two probabilities (crossing and collision) improves the prediction of wildlife fatality probability on roads. By using connectivity maps based on resistance surfaces as proxy of animal crossing probability and multiplying these values with collision probability based on traffic volume, vehicle and animal speed, vehicle width, and animal body size, we predicted fatality risk at a single road level for two small carnivore species (Lesser Grison and Molina's Hog-nosed Skunk). To validate the performance of the models, we used a road for which we had available road-kill data. Additionally, we compared the mitigation priority locations from our predictive models with the priority locations obtained from a road-kill hotspot analysis. We found that multiplicative integration of probabilities was not good to predict road-kills, and collision probability alone was better than crossing probability, at least for the Lesser Grison. Although the mitigation outcome of collision models was lower than hotspots, at least for the Lesser Grison, with a target of almost 10% of mitigated road, around 70% of road-kills of that species would be avoided, evidencing that the approach is a good alternative in a decision-making context.

Key-words: Road-kill, Connectivity, Traffic volume, Road mortality, Mitigation

Introduction

Reducing the direct impacts of roads on biodiversity is one of the most concerning issues in conservation biology research (van der Ree et al. 2015c). Among them, mortality by vehicle-animal collisions could have severe outcomes on some animal populations (Rytwinski & Fahrig 2011; Jackson & Fahrig 2011). Several kinds of mitigation measures and actions aim to minimise this mortality (Smith et al. 2015; van der Ree et al. 2015a). Some mitigation measures are focused on changing driver behavior, such as signs or speed controls (Huijser et al. 2015), whilst others focus on changing animal movement, e.g. wildlife crossing structures and fencing (Smith et al. 2015; van der Ree et al. 2015a). In common, the success of all those actions depends directly on choosing suitable locations to mitigate.

Mitigation location planning is a challenging task and most appropriate approaches are context dependent. Mostly, extensive road networks were implemented before environmental licensing emerged, so there is an important demand on road retrofitting for mortality mitigation and defragmentation (van der Grift 2005; Trocmé 2006; Gurrutxaga & Saura 2013). Further, developing countries are promoting a considerable road network expansion, with millions of kilometers being built and planned over the next half-century (Laurance et al. 2015). For retrofitting existing roads, it is possible to plan mitigation measures based on observational studies of road-kills or connectivity, however, this is only achievable at a single (or few) road segment level and not at an entire road network level, as often required. Regarding new roads, observational studies are not feasible at all. In both contexts the main challenge is to predict wildlife road fatalities without road-kill data.

The risk of a road-kill event can be expressed as the spatial and temporal coincidence of an animal being on a given road section (exposure risk) and a moving vehicle (hazard) (Visintin et al. 2016). Exposure risk or hereafter crossing probability is given by the probability of an animal to cross a road at a specific location, which is related to road and landscape configuration and to animal occurrence and movement (Lewis et al. 2011; Grilo et al. 2011, 2018; Gurrutxaga & Saura 2013; Thurfjell et al. 2015). Hazard, or collision probability hereafter, can be dependent on animal attributes (body length and road crossing speed) and road features including traffic volume, vehicle speed and road width (Hels & Buchwald 2001; van Langevelde & Jaarsma 2004; Jaarsma et al. 2006).

Until recently, few studies addressed the integration of crossing probability and collision probability to predict fatality risk in a single model (Jaarsma et al., 2007; Patrick et al., 2012; Visintin et al., 2017, 2016). These studies differed mainly in the ways crossing probability was assessed: as a result of occurrence likelihood (e.g. Visintin et al. 2016) or using movement simulations (e.g. Jaarsma et al., 2007). Yet only Visintin et al. (2017, 2016) and Patrick et al. (2012) validated model performances.

Our study aimed to evaluate if the integration of these two probabilities (crossing and collision) allows for the prediction of wildlife fatality probability on roads better than sub-models of each probability. We first used connectivity maps based on resistance surfaces as proxy of animal crossing probability and calculated collision probability based on traffic volume, vehicle and animal speed, vehicle width, and animal body size. Then, we multiplied crossing and collision probabilities to predict fatality risk at a single road level for two small carnivore species. We also tested univariate and bivariate models using both probabilities. To validate the model predictive performance, we used a road as a model system and two species for which we had available road-kill data. To test our model when translated into recommendations for mitigation location in a decision-making context, we used a simple cost-benefit analysis, which cost is represented by the proportion of the road that is mitigated and benefit corresponds to the proportion of avoided fatalities, assuming a perfect effectiveness of the hypothetic mitigation. Additionally, we compared the cost-benefit ratio of our predictive model to a conventional hotspot approach, using the same data set.

Methods:

Target Road and Species

Our study site was a 277-km road (BR-101; initial coordinates 30°9'1.20"S and 50°30'49.33"W, and final coordinates 32°0'23.64"S and 52°2'17.73"W, Appendix A) at southernmost Brazil. Our target species were Lesser Grison (*Galictis cuja)* and Molina's Hog-nosed Skunk (*Conepatus chinga*), two small carnivores, and we assumed that these two species do not avoid crossing the road. The Lesser Grison is a mid-sized mustelid (1.2–2.5 kg) of southern South America (Yensen & Tarifa 2003) and the Molina's Hog-nosed Skunk, a 2kg mephitid, is distributed from mid-northern Argentina and Chile to Bolivia, Paraguay, Uruguay and southern Brazil (Bornholdt et al. 2013). We divided the road into equally sized segments and obtained the crossing probability and the collision probability for each road segment for each species. To test for scale (grain size) dependency this procedure was repeated for multiple segment lengths: 1000 m, 500 m, and 275 m.

Crossing probability

Crossing probability for each road segment was obtained from maps that represent the expected connectivity between source patches for each species given the assigned resistance of surrounding land cover classes to their movement. To develop a resistance surface, we used a land cover map classified from 2009 LANDSAT 5 TM images (UFRGS-IB-Centro de Ecologia 2016) with 17 land cover/use classes: water, wetland, native forest (divided in size: < 1 ha, 1-10 ha, 11-100 ha, and > 100 ha), silviculture, rice monoculture, dry agriculture, outcrop, wet grassland, degraded grassland, dry grassland, urban area, mining, sand, and mixed areas. Mixed areas included multiple crops, annual or perennial. We queried experts on the natural history/ecology of the target species to help determine movement resistance values for each land cover class. We used the Analytic Hierarchy Process (Saaty 1987) by which experts make decisions using a series of pairwise comparisons among cover classes (see details in Appendix B). We checked the consistency of each expert's resistance assignment and used only assignments with a ratio between consistency index and random index lower than 0.1 (Saaty 1987).

We used native grassland remnants in a 25-km buffer surrounding the target road as source patches. This procedure was done in two scenarios: 1) using all grassland remnants (n=125) and 2) using only patches larger than 1 km^2 (n=74). In the second scenario, we assumed that areas smaller than 1 km^2 are less important as source patches due to limited resource quality and/or limited population density. This option is supported by a study in southern Brazil that estimated the average home-range for 12 Molina's Hog-nosed Skunk as 1.63 km^2 (Kasper et al. 2012).

We used connectivity maps based on circuit-theory and least-cost path to calculate crossing probability for each species at each road segment. We built the connectivity maps using circuit-theory in Gflow software (Leonard et al. 2017) and using least-cost corridor in Linkage Mapper (McRae & Kavanagh 2011). Circuit theory-based connectivity is modelled by assigning to each pixel in a landscape matrix a resistance value indicating the degree of landscape permeability for the electrons flow (or animals by analogy) (Leonard et al. 2017). Landscapes are represented as conductive surfaces, with low resistances assigned to landscape features that are most permeable to movement, and high resistances assigned to movement barriers (McRae et al. 2013). In the circuit-theory approach we used different criteria for the convergence factor, that is, a correlation factor of the current density between pairs of source patches (it defines the number of decimal places for the correlation threshold among intermediate connectivity maps; 1N corresponds to 0.9 and 4N correspond to 0.9999), and compared the results. The output of each circuit-theory model was a map with cell values that represented the total number of potential crossings (in amperes) between all pairwise source patches. We rescaled the cell values from 0 to 1 and sampled the mean value of all cells that intersected each road segment as the crossing probability.

For the second approach, we used normalized least-cost corridor distance which is the summation of cost-weighted distance rasters calculated from each pair of connected source patches. We rescaled the least-cost corridor distance values from 0 to 1 and inverted them as cells with small distances represent high crossing probabilities. For each species, we obtained four maps in Gflow software (both source patches scenarios and two convergence factors) and two maps in Linkage Mapper (both source patches scenarios). The maps were named based on the software used, source patch criteria and convergence factor (Gflow only) (Table 1). In the final models, we only used the maps with the best road-kill predictive performance for the species (further described in the Validation section). We did not use the Gflow connectivity map which considered source patches larger than 1 km^2 and a convergence factor of 4N because it was highly correlated with the one using a convergence factor of 1N (Pearson correlation of 0.85).

Table 1. Nomination of each crossing model according to adopted connectivity measure approach (software) and other criteria.

Model name	**Software**	**Source patch inclusion criteria**	**Convergence factor**
G-All-1	Gflow	all habitat areas (n=125)	1N
G-All-4	Gflow	all habitat areas (n=125)	4N
G-1	Gflow	habitat areas ≥ 1km^2	1N
L-All	Linkage Mapper	all habitat areas (n=125)	Not applicable

L-1	Linkage Mapper	habitat areas ≥ 1 km^2	Not applicable

Collision probability

For the collision probability at each road segment, we used the traffic volume, vehicle speed, animal speed, animal length, vehicle width, and road width following Hels & Buchwald (2001) and Jaarsma et al. (2006). We used the equation: 1-exp(-N*(a/v), where N is traffic volume; “a” is a kill zone (vehicle width + animal length *2 if a two-lane road), and “v” is the animal speed. We used vehicle counters (Vehicle Counter Generation III - TRAFx Research Ltd.) to calculate the average daily traffic (ADT) in three locations linking the main regional settlements: Capivari do Sul (n=48 days), Mostardas (n=273 days), and São José do Norte (n=498 days) along BR 101. Since we found a north-to-south decrease pattern in traffic volume, we extrapolated traffic volume for each road segment by performing a linear regression with the recorded ADT at each surveyed location and the distance to the northernmost city (Capivari do Sul). We used a mean vehicle width of 1.8 m that represented a small automobile, the most common vehicle on this road. For Molina's Hog-nosed Skunk, we used a body length of 0.40 m (Kasper et al. 2011) and we used half of the fastest recorded speed (116 m/min) for a similarly sized and related species (*Mephitis mephitis*) (Hirt et al. 2017). We also tested collision probability using 25% of the maximum recorded speed as suggested by Jaarsma et al. (2006), however, it was highly correlated to the collision probability using the half speed. For Lesser Grison, we used a body length of 0.42 m (Jones et al. 2009) and a recorded speed for related species (*Martes foina*) which was 100 m/min (Posillico et al. 1995).

Fatality probability and Validation

We multiplied crossing probability and collision probability to obtain a fatality probability for each road segment. To test the predictive performance of the models, we used 64 road-kills of Lesser Grison and 159 road-kills of Molina's Hog-nosed Skunk from a road-kill survey carried out on the same road (Appendix A). The data set was obtained based on monthly surveys conducted from September 2012 to August 2014, and from February to October 2015, totaling 33 surveys. Two observers (including the driver) conducted surveys by car at 40-50 km/h from dawn to dusk. We fitted four Poisson models to the data using the number of observed road-kills on each segment for each species: crossing model, collision model, fatality model and crossing and collision in the same model (bivariate). For the crossing model, we selected one map among the five connectivity outcomes based on their predictive performance (Table 2).

We cross-validated the models by randomly splitting the data into 10 folds (nine subsets used for training the model and one for testing the model fit). We repeated this procedure 100 times for each model. We obtained the mean absolute error (MAE) to assess the model predictions (Willmott & Matsuura 2005; Chai & Draxler 2014). MAE varies between zero and the highest observed number for each sampling unit (Lesser Grison - six road-kills for 1 km road length and four for 500 m and 275 m lengths; Molina's Hog-nosed Skunk - six road-kills for 1 km and 500 m road length and four for 275 m). We also compared the Akaike information criterion (AIC) of each model for each species. We performed these analyses by using the *train* function in the *caret* package (Kuhn 2008) in the R environment (R Core Team 2017).

Decision support outcome of models

We simulated a mitigation planning scenario and compared the performance of different models using a cost-benefit approach similar to that previously used by Ascensão et al.

(2017) and Gonçalves et al. (2018). For multiple road segment sizes (1000, 500 and 275 meters) and for multiple thresholds of percentage of road mitigated (cost proxy), we estimated how many fatalities (% of observed carcasses) of each species would be avoided (benefit proxy). We assumed that mitigation would be 100% effective. For each segment size, the first cost threshold was defined using the number of segments prioritized by a hotspot analysis (see below). The following thresholds were arbitrarily defined as 2 and 3 times the number of segments of the first one. For each model, we selected the segments with the largest predicted probabilities until the target threshold cost was achieved.

Hotspot number and location was obtained in a two-step analysis. Firstly, we checked if road-kill aggregation is significant at the selected segment lengths (1000, 500 and 275 m) with Ripley’s K statistics (Ripley 1981). We then performed a 2D HotSpot Identification analyses using half of the segment length as the radius and 1000 simulations. We considered as hotspots all segments with a road-kill intensity value higher than the upper confidence limit of 95% (Coelho et al., 2014). For both analyses we used Siriema software (Coelho et al. 2014).

Results

Different crossing models were selected for the two species (Table 2). The circuit-theory approach using areas larger than 1 km^2 as source patches was the best connectivity map for the Lesser Grison (Table 2) whereas least-cost corridor using all source patches was the best for Molina's Hog-nosed Skunk (Table 2). We used these crossing models to build the final fatality models (Figure 1 and 2).

Table 2: Predictive performance results for each crossing model for each species (Lesser Grison - *Galictis cuja* and Molina's Hog-nosed Skunk - *Conepatus chinga*) and segment length (1000 m, 500 m, and 275 m). MAE is the mean absolute error, SD is the standard deviation of mean absolute error, and AIC is the Akaike Information Criteria.

	Segment length					
	1000 m		500 m		275 m	
	MAE (SD)	AIC	MAE (SD)	AIC	MAE (SD)	AIC
Lesser Grison						
G-1	**0.30 (0.11)**	**255.53 (0.17)**	**0.17 (0.05)**	**317.48 (0.10)**	**0.10 (0.02)**	**382.85**
G-All-4	0.34 (0.11)	281.23 (0.18)	0.18 (0.05)	342.46 (0.11)	0.11 (0.02)	407.5
G-All-1	0.34 (0.11)	285.41 (0.18)	0.18 (0.05)	347.39 (0.11)	0.11 (0.02)	411.74
L-All	0.41 (0.11)	377.54 (0.17)	0.21 (0.05)	438.4 (0.12)	0.12 (0.02)	504.19
L-1	0.41 (0.11)	378.40 (0.17)	0.21 (0.05)	439.04 (0.12)	0.12 (0.02)	504.33
Molina's Hog-nosed Skunk						
L-All	**0.69 (0.10)**	**569.73 (0.44)**	**0.44 (0.07)**	**750.32 (0.27)**	**0.27 (0.03)**	**900.82**
L-1	0.70 (0.10)	575.50 (0.44)	0.44 (0.07)	753.72 (0.27)	0.27 (0.03)	904.34
G-All-4	0.79 (0.08)	630.56 (0.47)	0.47 (0.06)	810.98 (0.28)	0.28 (0.03)	961.24
G-1	0.79 (0.08)	630.83 (0.47)	0.47 (0.07)	811.28 (0.28)	0.28 (0.03)	961.77
G-All-1	0.80 (0.08)	638.82 (0.47)	0.47 (0.07)	819.71 (0.28)	0.28 (0.03)	969.56

Spatial distribution of collision probabilities showed a similar pattern for both species, however crossing and fatality probabilities, road-kills and hotspots were different (Figure 1 and Appendix C). Predictive performances were also different among species (Figure 2). For Lesser Grison, for all road lengths, collision models and bivariate models, which considered crossing and collision, had the lowest mean absolute errors (Figure 2), but collision models presented the lowest AIC (Table 3). Fatality models performed the worst at predicting road-kill fatalities on BR-101 road for Lesser Grison (Table 3). Although, bivariate model was better than other models to predict road-kills for Molina's Hog-nosed Skunk, for all road lengths, (Figure 2 and Table 3), all models were very similar, except the crossing model which had the highest mean absolute error (Table 3). Mean absolute errors were lower with decreasing segment size for all models and for both species (Figure 2).

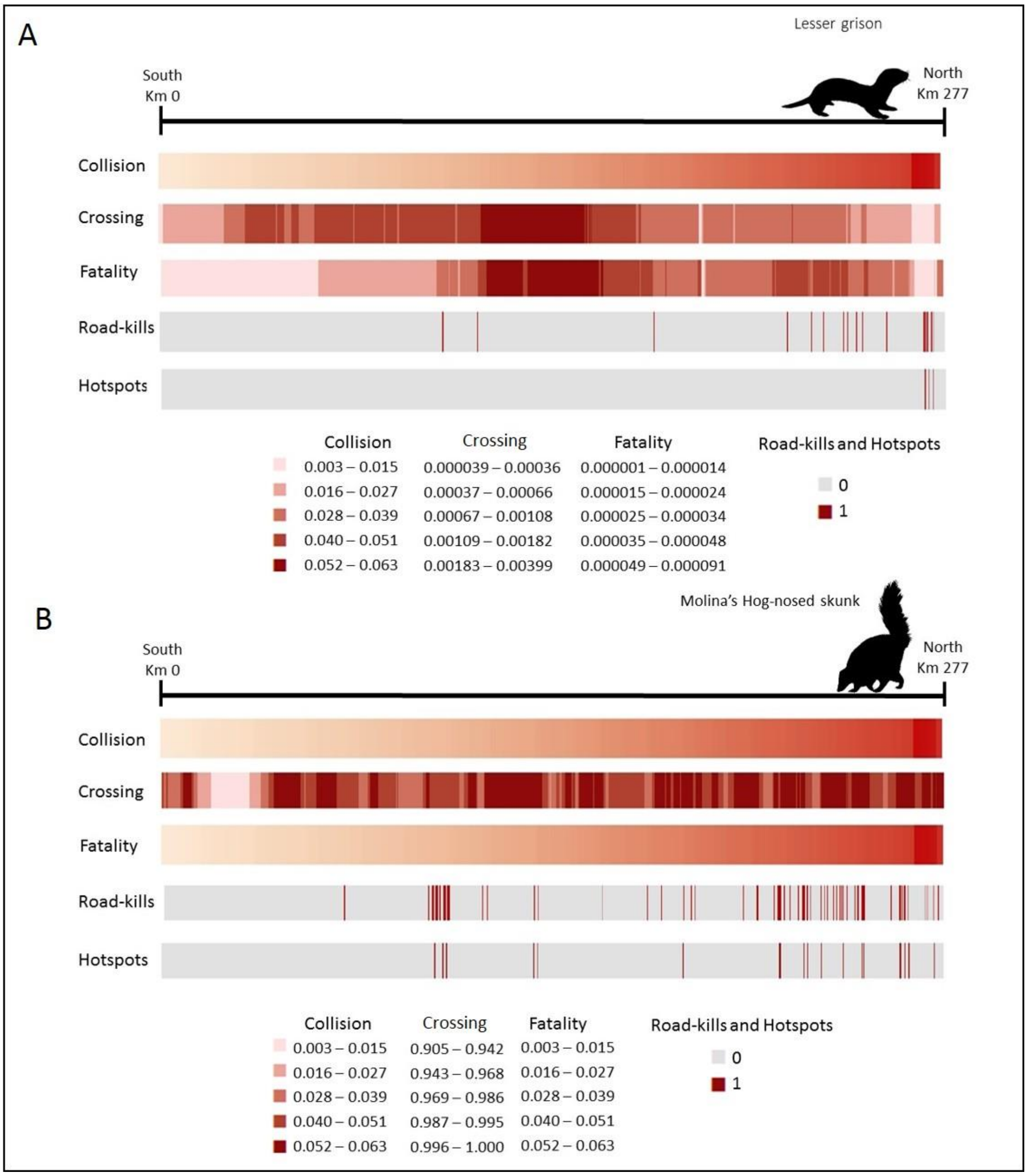

Figure 1: Collision, Crossing and Fatality probabilities, road-kill records and Hotspots for Lesser Grison (A) and Molina's Hog-nosed Skunk (B) for segment length of 275 m along BR-101.

Table 3: Akaike Information Criteria of the four models (Collision, Crossing, Crossing + Collision, and Fatality) for each species (Lesser Grison - *Galictis cuja* - and Molina's Hog-nosed Skunk - *Conepatus chinga*) and each segment length (1000 m, 500 m, and 275 m).

	AIC		
	1000 m	500 m	275 m
Lesser Grison			
Crossing	255.53	317.48	382.85
Collision	**232.11**	**292.54**	**358**
Fatality	346.46	407.38	472.58
Crossing + Collision	233.91	294.4	359.81
Molina's Hog-nosed Skunk			
Crossing	569.73	750.32	900.82
Collision	530.74	711.56	861.51
Fatality	529.95	710.72	860.66
Crossing + Collision	**517.07**	**697.04**	**847.06**

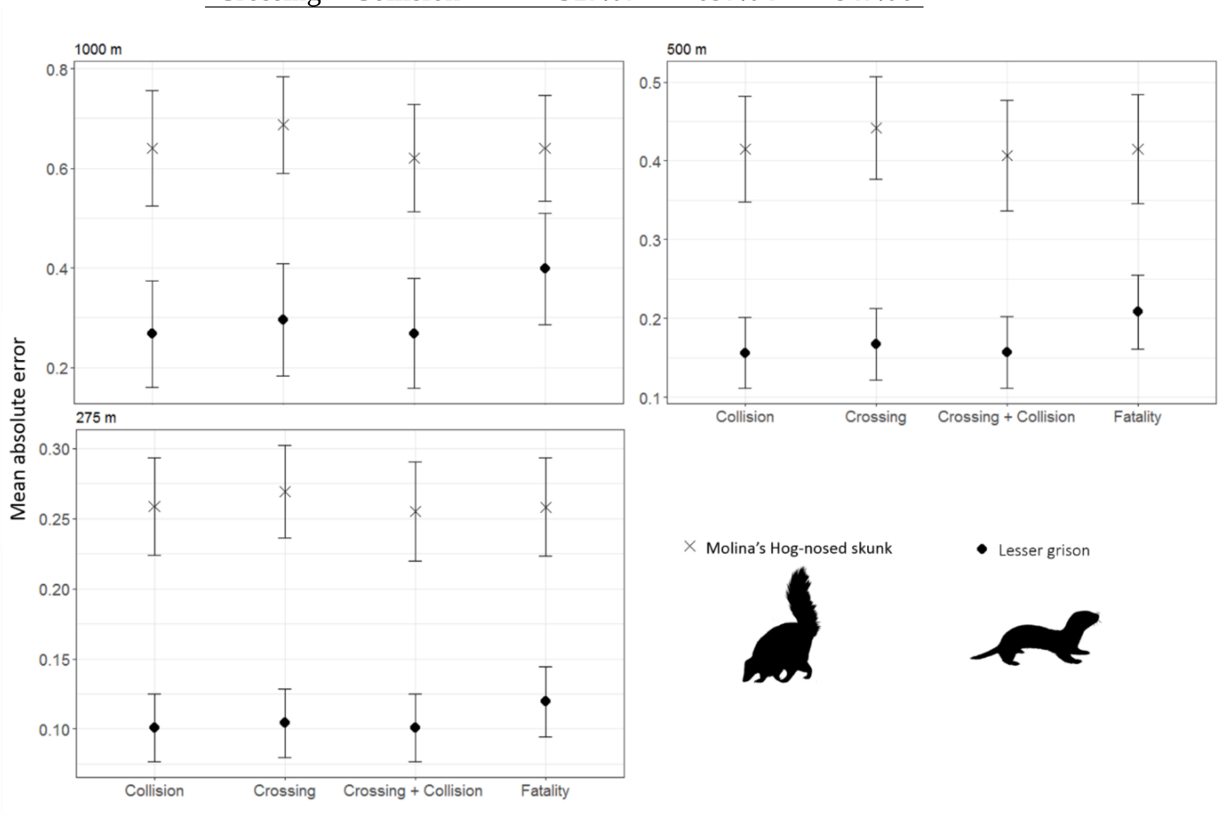

Figure 2: Mean absolute error of predictive models for each species: Lesser Grison (*Galictis cuja)* and Molina's Hog-nosed Skunk (*Conepatus chinga)*. We presented four

models (Collision, Crossing, Crossing + Collision, and Fatality) for the three different segment sizes: 1000 m (left above), 500 m (right above) and 275 m (below).

Crossing models, even with a good predictive performance, were not good at planning spatial placements of mitigation structures, especially for the Lesser Grison (Table 4). As expected, given the predictive performance of collision models, the potential mitigation outcome for the Molina's Hog-nosed Skunk was smaller than for the Lesser Grison. The best cost-benefit ratio (% of mitigated road divided by the % of fatalities avoided) resulted from predictive models for the Molina's Hog-nosed Skunk and was 1:2.6 whereas for the Lesser Grison the best ratio was 1:14.1 (Table 4).

Although the mitigation outcome of collision models was in general lower than the one resulting from hotspot analyses, at least for the Lesser Grison, with a target of almost 10% of mitigated road (segment size of 1000 m in Table 4), around 70% of road-kills of that species would be avoided. Additionally, for this species, the cost-benefit ratio did not change among road segment sizes (nearly 1:7 with a 5% road mitigation effort; Table 4).

Table 4: Percentage of recorded road-kills that could be avoided if mitigation was planned considering hotspots analyses, or collision, crossing, and fatality predictive models for each species (Lesser Grison - *Galictis cuja* and Molina's Hog-nosed Skunk - *Conepatus chinga*), for multiple segment sizes and multiple thresholds of percentage of mitigated road. At hotspots column, the first threshold was the number segments which were identified as hotspots, so there was no percentage of fatalities avoided for the other two thresholds of number of segments.

			Lesser Grison						*Molina's Hog-nosed Skunk*			
			% of fatalities avoided						**% of fatalities avoided**			
Segment size	**number of segments**	**% road**	**hotspots**	**collision**	**crossing**	**fatality**	**number of segments**	**% road**	**hotspots**	**collision**	**crossing**	**fatality**
1000 m	13	4.7	62.50	35.94	0	0	19	7	39.62	10.69	13.21	10.69
	26	9.5	-	68.75	0	0	38	14	-	35.85	22.01	35.85
	39	14	-	79.69	0	0	57	20.7	-	49.06	33.96	49.06
500 m	10	1.8	29.69	21.88	0	0	35	6.35	28.93	6.29	6.29	6.29
	20	3.6	-	34.38	0	0	70	12.7	-	31.45	20.75	31.45
	30	5.4	-	35.94	0	0	105	19	-	45.28	25.16	45.28
275 m	10	1	21.88	14.06	0	0	38	3.8	18.87	1.89	5.66	1.89
	20	2	-	26.56	0	0	76	7.6	-	11.32	10.06	11.32
	30	3	-	28.13	0	0	114	11.4	-	23.90	18.24	23.90

Discussion

Our approach demonstrated that we can predict road-kill risk using traffic volume as a main predictor and that connectivity has a potential use for modelling road-kill risk for some species. As traffic volume information at a single road could be relatively easily measured with traffic counters and/or modelled and is an important determinant of wildlife-vehicle collisions (Gunson et al. 2011), we considered the use of our collision probability equation as a good alternative for predicting road-kills in the absence of road-kill data.

Our collision model, however, used the same animal speed and, for a given species, this value could change depending on traffic volume (Jacobson et al. 2016). Traffic volume was the main predictor because it was the only variable that changed along the road segments. Other variables may be incorporated into the equation, such as vehicle speed (Jaarsma et al. 2006). Vehicle speed has also been documented as a relevant predictor for wildlife collisions (Gunson et al. 2011) however, it is more difficult to obtain or model for all road segments. Another potential limitation of the collision probability equation is the exponential relationship between road-kill probability and traffic volume (Litvaitis & Tash 2008). It has been shown for some species that the highest road-kill risk is observed with an intermediate traffic volume, since animals are likely to avoid crossing the road when the traffic is too high (Jacobson et al. 2016). Although our modelled traffic varied from 140 to 2.500 vehicles/day, the higher level is still within the range of what is generally recognized as low traffic (van Langevelde & Jaarsma 2004; Sadleir & Linklater 2016), so we assumed that road avoidance not influenced our results.

The predictive performance of models using crossing probability based on connectivity maps was worse than models using the collision probability equation for both species. The relationship between crossing probability and road-kills for the Lesser Grison was contrary to expectation; the highest crossing probabilities were at locations with no road-kills which could result in poor mitigation decisions. This inverse relationship can be biased by species occurrence since we did not consider this variable to improve the selection of our source patches and calculate connectivity. Differences in species occurrence may modify the connectivity pattern.

The use of expert opinion as a tool for building resistance maps can have limitations as an overestimation of the importance of some habitats (Clevenger et al. 2002), however it can be suitable for species with strong habitat preferences. Further, subjectivity on resistance assignment could be controlled with the Analytical Hierarchy Process used (Saaty 1987). It has already been used for predicting wildlife fatalities on roads (Hurley et al. 2009).

To improve the accuracy of connectivity mapping and, consequently, crossing probability on roads, an alternative is to obtain movement data by telemetry, (Bastille-Rousseau et al. 2018). Although telemetry is becoming cheaper and more popular, it is still very difficult to implement for multiple species and study sites. Another possible improvement for crossing probability estimation may be obtained by also incorporating the traffic volume as another layer in our resistance map (Dutta et al. 2016). Our connectivity modelling approach is simple and potentially applicable to other roads or at the road network scale and could possibly be improved if source patches could be modelled from presence-absence, occurrence or occupancy modelling approach (Mackenzie et al. 2006; Guillera-Arroita 2017).

We proposed the fatality probability (multiplication of crossing probability and collision probability) based on the logic of collision events – animals and moving vehicles must coincide in space and time. However, the fatality probability was not good at predicting road-kills for our target species. Bivariate models (additive) had a better predictive performance, although not considerably better than the univariate collision model. This apparently results from the poor performance of crossing models possibly due to low accuracy of source patch assignment. No other single road study integrated the two sub-models (crossing and collision) in this manner, therefore comparison with other studies is difficult due to variation in the use of different statistics to measure predictive performance. Jaarsma et al. (2007) proposed a very similar idea using an animal simulation movement approach, but they did not validate their models. Although, new roads are specially challenging for road-kill mitigation (van der Ree et al. 2015b), and traffic seems to be a very important variable to predict where road-kill risk is higher, the approach described here may be applicable for modelling and predicting traffic volume using variables such as human population density, distance to main cities or main roads, and road class (Visintin et al. 2016),

Our cost-benefit analysis demonstrated that, at least for one of our target species, the collision model could identify potentially effective mitigation locations with a good benefit-cost ratio for any evaluated road segment size (scale). Thus, our approach may be useful to apply to roads where road-kill data are not available or on large road networks as well. Road retrofitting or new road construction are two contexts that demand a move of road ecology from a tradition of descriptive approaches to the development of predictive tools able to provide management recommendations with few or no data.

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Supplementary material

Appendix A. KML file with road track, road-kill records, road-kill hotspots, crossing probability, collision probability of Lesser Grison (*Galictis cuja)* and Molina's Hog-nosed Skunk (*Conepatus chinga*).

Appendix B. Explanation for how we obtained the resistance value based on expert opinion and Analytic Hierarchy Process.

We used the Analytic Hierarchy Process to facilitate decision making about resistance values. Experts determined resistance values by a series of pairwise comparisons based on Saaty (1987).

Experts' responses varied from 1 to 9 and were based on the comparison between land use classes. The larger the score is, more resistant to kangaroo movement is that class:

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two classes contribute equally for the goal
3	Moderate importance of one over another	Experience and judgement slightly favour one class over another
5	Essential or strong importance	Experience and judgement strongly favor one class over another
7	Very strong importance	A class is strongly favoured and its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one class over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgements	When compromise is needed

Table below showed the 17 classes of land cover used obtained from UFRGS-IB-Centro de Ecologia (2016):

Code	**Land cover**
A	Water
B	Rock outcrop
C	Sand
D	Wetland
E	Native forest < 1 ha
F	Native forest 1-10 ha
G	Native forest 11 - 100 há
H	Native forest > 100 ha
I	Dry grassland
J	Wet grassland
L	Degraded grassland
M	Silviculture
N	Mixed areas
O	Dry agriculture
P	Rice monoculture
Q	Mining
R	Urban area

Three experts gave values for each class based on the pairwise comparison (one value per class). We present result for one expert in the table below. The value in each cell of the table below corresponds to the result of the pairwise comparison. All comparisons were always made between rows and columns in this order. For example, class A is five times more resistant than class G. Consequently, class G is five times less resistant than class A (1/5=0.20).

Code	A	B	C	D	E	F	G	H	I	J	L	M	N	O	P	Q	R
A	1.00	2.00	2.00	3.00	7.00	7.00	5.00	3.00	9.00	9.00	7.00	7.00	6.00	5.00	7.00	3.00	2.00
B	0.20	1.00	1.00	0.50	1.00	0.50	0.20	0.14	3.00	3.00	1.00	1.00	1.00	0.50	3.00	0.33	0.20
C	0.20	1.00	1.00	1.00	1.00	0.50	0.33	0.14	3.00	3.00	2.00	1.00	1.00	0.50	2.00	0.33	0.20
D	0.33	2.00	1.00	1.00	1.00	0.50	0.33	0.20	3.00	3.00	2.00	1.00	1.00	1.00	2.00	0.33	0.20

E	0.14	1.00	1.00	1.00	1.00	0.50	0.20	0.14	3.00	3.00	1.00	0.50	0.50	0.50	1.00	0.33	0.20
F	0.14	2.00	2.00	2.00	2.00	1.00	0.33	0.17	5.00	5.00	3.00	1.00	1.00	1.00	2.00	1.00	0.33
G	0.20	5.00	5.00	3.00	5.00	3.00	1.00	0.20	5.00	5.00	4.00	2.00	2.00	1.00	5.00	2.00	0.50
H	0.33	7.00	7.00	5.00	7.00	6.00	5.00	1.00	9.00	9.00	7.00	3.00	3.00	2.00	7.00	3.00	1.00
I	0.11	0.33	0.33	0.33	0.33	0.20	0.20	0.11	1.00	1.00	0.50	0.50	0.50	0.33	0.50	0.33	0.14
J	0.11	0.33	0.33	0.33	0.33	0.20	0.20	0.11	1.00	1.00	0.50	0.50	0.50	0.33	0.33	0.33	0.14
L	0.14	1.00	0.50	0.50	1.00	0.33	0.25	0.14	2.00	2.00	1.00	1.00	1.00	0.50	1.00	0.50	0.20
M	0.14	1.00	1.00	1.00	2.00	1.00	0.50	0.33	2.00	2.00	1.00	1.00	1.00	0.50	2.00	0.50	0.20
N	0.17	1.00	1.00	1.00	2.00	1.00	0.50	0.33	2.00	2.00	1.00	1.00	1.00	1.00	2.00	0.50	0.20
O	0.20	2.00	2.00	1.00	2.00	1.00	1.00	0.50	3.00	3.00	2.00	2.00	1.00	1.00	3.00	1.00	0.33
P	0.14	0.33	0.50	0.50	1.00	0.50	0.20	0.14	2.00	3.00	1.00	0.50	0.50	0.33	1.00	0.33	0.20
Q	0.33	3.00	3.00	3.00	3.00	1.00	0.50	0.33	3.00	3.00	2.00	2.00	2.00	1.00	3.00	1.00	0.33
R	0.50	5.00	5.00	5.00	5.00	3.00	2.00	1.00	7.00	7.00	5.00	5.00	5.00	3.00	5.00	3.00	1.00

On the next step, all cell values were divided by the sum of its specific column resulting in the table below:

Code	A	B	C	D	E	F	G	H	I	J	L	M	N	O	P	Q	R
A	0.23	0.06	0.06	0.10	0.17	0.26	0.28	0.38	0.14	0.14	0.17	0.23	0.21	0.26	0.15	0.17	0.27
B	0.05	0.03	0.03	0.02	0.02	0.02	0.01	0.02	0.05	0.05	0.02	0.03	0.04	0.03	0.06	0.02	0.03
C	0.05	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.05	0.05	0.05	0.03	0.04	0.03	0.04	0.02	0.03
D	0.08	0.06	0.03	0.03	0.02	0.02	0.02	0.03	0.05	0.05	0.05	0.03	0.04	0.05	0.04	0.02	0.03
E	0.03	0.03	0.03	0.03	0.02	0.02	0.01	0.02	0.05	0.05	0.02	0.02	0.02	0.03	0.02	0.02	0.03
F	0.03	0.06	0.06	0.07	0.05	0.04	0.02	0.02	0.08	0.08	0.07	0.03	0.04	0.05	0.04	0.06	0.05
G	0.05	0.14	0.15	0.10	0.12	0.11	0.06	0.03	0.08	0.08	0.10	0.07	0.07	0.05	0.11	0.11	0.07
H	0.08	0.20	0.21	0.17	0.17	0.22	0.28	0.13	0.14	0.14	0.17	0.10	0.11	0.10	0.15	0.17	0.14
I	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.02	0.02	0.02	0.01	0.02	0.02
J	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.02	0.02	0.02	0.01	0.02	0.02
L	0.03	0.03	0.01	0.02	0.02	0.01	0.01	0.02	0.03	0.03	0.02	0.03	0.04	0.03	0.02	0.03	0.03
M	0.03	0.03	0.03	0.03	0.05	0.04	0.03	0.04	0.03	0.03	0.02	0.03	0.04	0.03	0.04	0.03	0.03
N	0.04	0.03	0.03	0.03	0.05	0.04	0.03	0.04	0.03	0.03	0.02	0.03	0.04	0.05	0.04	0.03	0.03
O	0.05	0.06	0.06	0.03	0.05	0.04	0.06	0.06	0.05	0.05	0.05	0.07	0.04	0.05	0.06	0.06	0.05
P	0.03	0.01	0.01	0.02	0.02	0.02	0.01	0.02	0.03	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.03
Q	0.08	0.09	0.09	0.10	0.07	0.04	0.03	0.04	0.05	0.05	0.05	0.07	0.07	0.05	0.06	0.06	0.05
R	0.11	0.14	0.15	0.17	0.12	0.11	0.11	0.13	0.11	0.11	0.12	0.17	0.18	0.15	0.11	0.17	0.14

Finally, we calculated the weight, lambda and relative weight (resistance values) following the equations indicated in the table below:

Land Cover Code	Sum of rows	Sum of columns	Weight (sum of rows/number of classes)	λ (weight/sum of columns)	Relative Weight (Resistances)

A	3.28	4.40	0.19	0.85	100.00
B	0.52	35.00	0.03	1.06	15.75
C	0.54	33.67	0.03	1.08	16.59
D	0.64	29.17	0.04	1.09	19.39
E	0.44	41.67	0.03	1.08	13.52
F	0.84	27.23	0.05	1.34	25.55
G	1.48	17.75	0.09	1.55	45.26
H	2.67	8.00	0.16	1.26	81.44
I	0.24	63.00	0.01	0.89	7.35
J	0.24	64.00	0.01	0.89	7.24
L	0.42	41.00	0.02	1.01	12.82
M	0.56	30.00	0.03	0.99	17.08
N	0.59	28.00	0.03	0.97	18.03
O	0.86	19.50	0.05	0.99	26.32
P	0.37	46.83	0.02	1.01	11.21
Q	1.03	17.83	0.06	1.08	31.45
R	2.30	7.39	0.14	1.00	70.11

We checked the consistency between comparisons based on the equation $CI = (\sum \lambda - n)/(n-1)$ where "n" is the number of classes and "λ" is obtained from the table above. Our Consistency Index (CI) equals 0.071.

To evaluate if the consistency is acceptable or not, we also calculated a Consistency Ratio as $CR = CI/RI$. The CR is obtained by comparing the CI with an average random consistency index (RI) (Saaty, 1987). If CR it is not lower than 0.10, experts must revise their judgments related to pairwise comparisons. The RI for 17 variables is 1.61 (Saaty, 1987). We calculated the CR as 0.044 and, thus, we accepted and used the experts evaluation for each cover class resistance in the connectivity map.

That was one example for one assignment of one expert. Below we present a table with the consistency index (CI) of the three experts for two target species:

Expert	Lesser Grison	Molina's Hog-nosed Skunk
1	0.044	0.044
2	0.085	0.186
3	0.116	0.379

For Lesser Grison, two experts were consistent in their evaluation (CI<0.1). Resistance values provided by these experts were correlated (0.90), so we used the mean of resistance values between them. For Molina's Hog-nosed Skunk only one expert was consistent, so we used the resistances gave for this expert.

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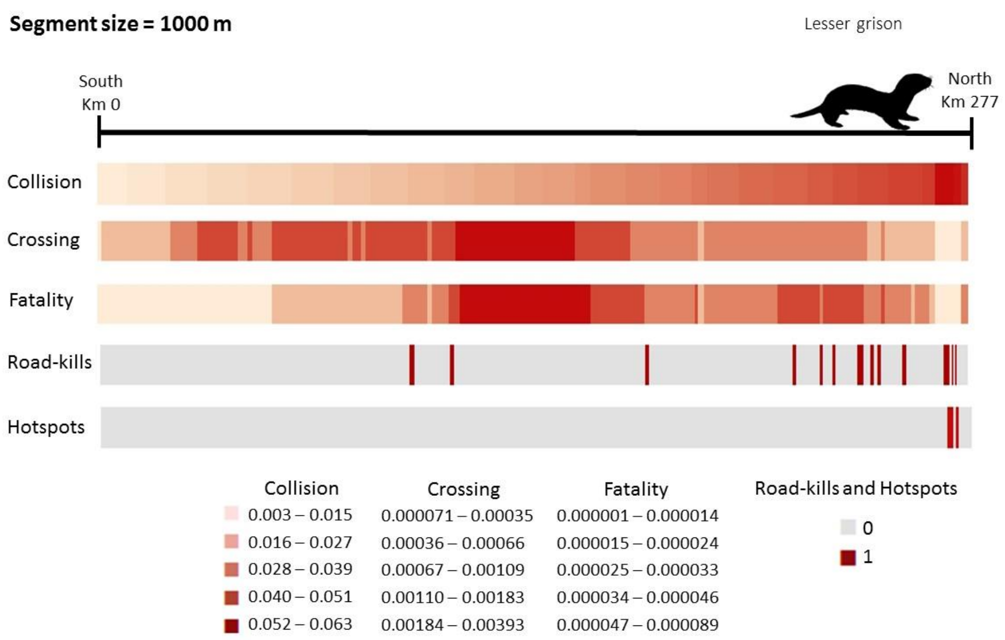
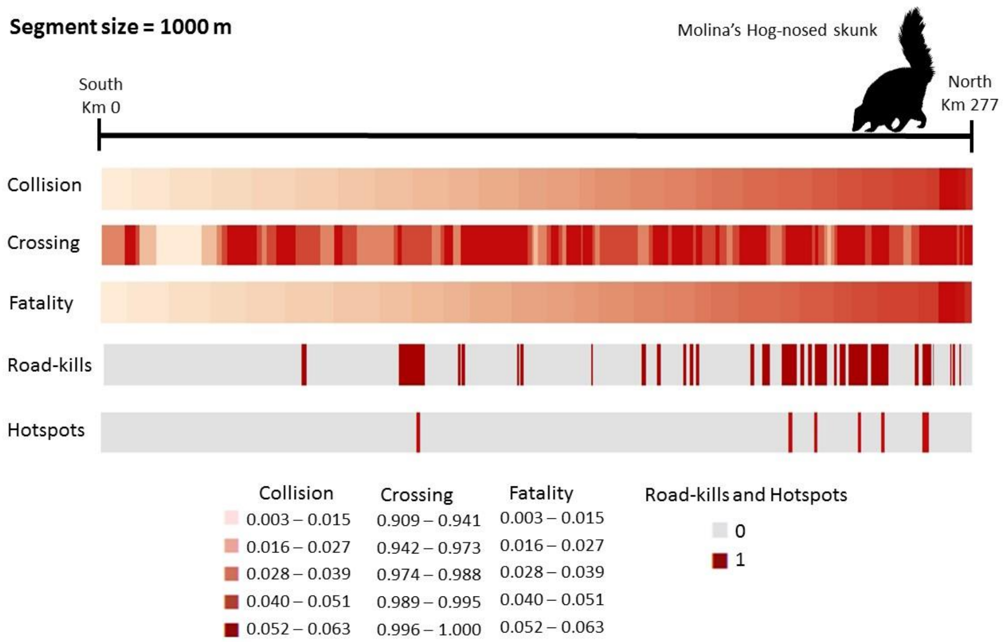
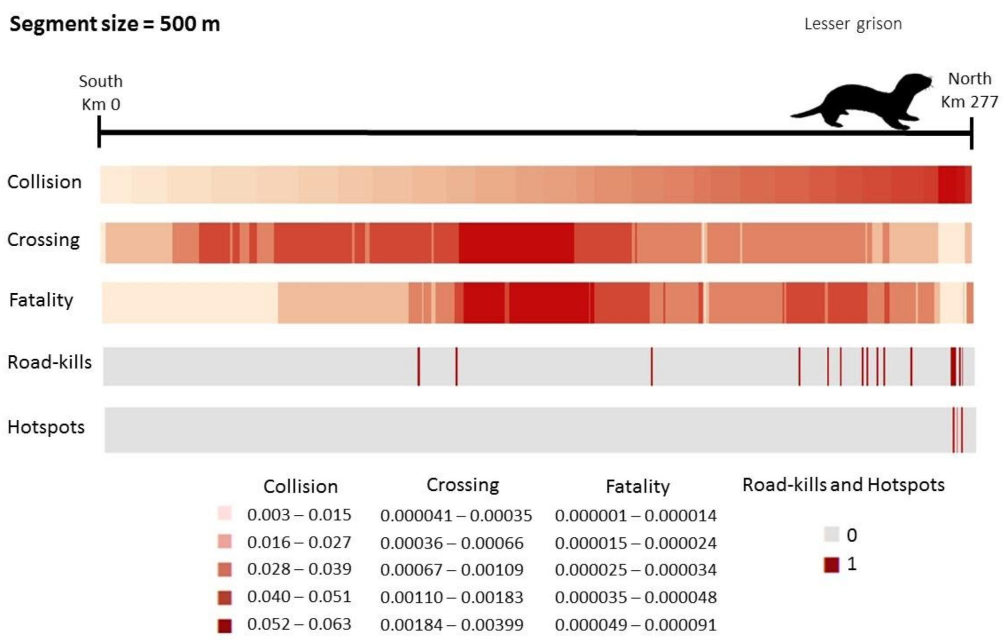
Appendix C. Crossing, Collision and Fatality probabilities, Road-kill records and Road-kill Hotspots for Lesser Grison (*Galictis cuja)* and Molina's Hog-nosed Skunk (*Conepatus chinga*) along BR-101 for 1000 m and 500 m of segment length.


Segment size = 1000 m
Lesser grison
South
Km 0
North
Km 277
Collision
Crossing
Fatality
Road-kills
Hotspots
Collision
0.003 – 0.015
0.016 – 0.027
0.028 – 0.039
0.040 – 0.051
0.052 – 0.063
Crossing
0.000071 – 0.00035
0.00036 – 0.00066
0.00067 – 0.00109
0.00110 – 0.00183
0.00184 – 0.00393
Fatality
0.000001 – 0.000014
0.000015 – 0.000024
0.000025 – 0.000033
0.000034 – 0.000046
0.000047 – 0.000089
Road-kills and Hotspots
0
1


Segment size = 1000 m
Molina's Hog-nosed skunk
South
Km 0
North
Km 277
Collision
Crossing
Fatality
Road-kills
Hotspots
Collision
0.003 – 0.015
0.016 – 0.027
0.028 – 0.039
0.040 – 0.051
0.052 – 0.063
Crossing
0.909 – 0.941
0.942 – 0.973
0.974 – 0.988
0.989 – 0.995
0.996 – 1.000
Fatality
0.003 – 0.015
0.016 – 0.027
0.028 – 0.039
0.040 – 0.051
0.052 – 0.063
Road-kills and Hotspots
0
1



Segment size = 500 m
Lesser grison
South
Km 0
North
Km 277
Collision
Crossing
Fatality
Road-kills
Hotspots
Collision
0.003 – 0.015
0.016 – 0.027
0.028 – 0.039
0.040 – 0.051
0.052 – 0.063
Crossing
0.000041 – 0.00035
0.00036 – 0.00066
0.00067 – 0.00109
0.00110 – 0.00183
0.00184 – 0.00399
Fatality
0.000001 – 0.000014
0.000015 – 0.000024
0.000025 – 0.000034
0.000035 – 0.000048
0.000049 – 0.000091
Road-kills and Hotspots
0
1

585

Segment size = 500 m
Molina's Hog-nosed skunk
South
Km 0
North
Km 277
Collision
Crossing
Fatality
Road-kills
Hotspots
Collision
0.003 – 0.015
0.016 – 0.027
0.028 – 0.039
0.040 – 0.051
0.052 – 0.063
Crossing
0.906 – 0.944
0.945 – 0.971
0.972 – 0.987
0.988 – 0.995
0.996 – 1.000
Fatality
0.003 – 0.015
0.016 – 0.027
0.028 – 0.039
0.040 – 0.051
0.052 – 0.063
Road-kills and Hotspots
0
1

586

Capítulo 3

Predizendo fatalidades em rodovias em uma rede de estradas usando as probabilidades de travessia e colisão

Este capítulo será submetido como research paper para a revista Biodiversity and Conservation e foi feito em colaboração com Casey Visintin e Rodney van der Ree. Ele está formatado conforme as normas dessa revista.

Predicting road fatalities at a road network using crossing and collision probabilities

Abstract

There is an urgent demand to predict wildlife-vehicle collisions at a regional scale due to the extension and expansion of road networks worldwide. On these networks it is often unfeasible to obtain road-kill data for mitigation planning. We predicted road-kills of the eastern grey kangaroo (*Macropus giganteus*) for Victoria roads (South-eastern Australia) based on the integration of crossing probability (exposure) and collision probability (hazard). We estimated crossing probability with connectivity maps using occurrence likelihood of the species as source areas and landscape resistance to movement based on experts' opinion. We estimated collision probability using models fit to traffic volume, road width, and animal speed when crossing a road. Both a standard equation and an alternative equation that included a road avoidance parameter were tested to model collision probability. Several model variations were validated using spatial locations of known road-kills through cross-validation. The best model was bivariate which used crossing and collision sub-models calculated with the avoidance factor. We discuss possible improvements to the crossing and collision sub-models that may increase the predictive performance of the integrated model.

Key-words: connectivity, expert opinion, road-kill, wildlife-vehicle collisions, road mortality

Introduction

There is a massive and dense road and railroad network worldwide (Laurance and Balmford 2013) and it causes several environmental impacts (van der Ree et al. 2015a) such as landscape modification, environmental degradation and direct wildlife mortality (van der Ree et al. 2015b). Road and railroad fatalities may result in negative consequences for both wildlife population persistence and human safety (van der Ree et al. 2015b), as they can cause notable economic damage, mainly on roads (Huijser et al. 2009). Therefore, implementing structures and actions for mitigation are necessary to avoid wildlife-vehicle collisions.

Due to the extent of national or regional road networks (CIA 2016) and the potential cumulative effects of wildlife-vehicle collisions on animal populations (Fahrig and Rytwinski 2009; Ceia-Hasse et al. 2018), regional scale planning of mitigation is important. At this scale, observational studies are often unfeasible or extremely costly for most species, except for those which cause high economic losses or injuries to humans – connected to road accidents (Danks and Porter 2010; Found and Boyce 2011) – or for those which are detected and reported by drivers such as open citizen science repositories; for example, the Taiwan Roadkill Observation Network (https://roadkill.tw/en) or California Roadkill Observational System (http://www.wildlifecrossing.net/california/). On a regional scale, the use of predictive models is almost a commitment.

In many scientific areas, statistical models are used mostly for causal explanation, and models that possess high explanatory power are often assumed to inherently possess predictive power (Shmueli 2010). However, explanatory and predictive models investigate different questions in different ways. Explanatory models correspond to the use of statistical models for testing correlation between variables and predictive modeling is the process of applying a statistical model for predicting new or future observations

(Shmueli 2010). In road ecology, it is not different. There is vast array of explanatory studies (Gunson et al. 2011), however, few predict to new data and have been developed to plan mitigation measures for reducing road-kills and/or increase connectivity (Dussault et al. 2007; Lewis et al. 2011; Nelli et al. 2018). Further, most studies have been conducted at a local scale or did not validate the predictions (Jaarsma et al. 2007; Patrick et al. 2012). There is still a need for improving road-kill prediction risk at a regional scale.

Visintin et al. (2016) proposed a framework for predictive models for road-kills which integrated two hierarchically related processes on roads: animal presence on the road (exposure risk, according to authors' definition), indicated by species occurrence, and collision probability (hazard according to authors' definition), represented by traffic volume and vehicle speed. Combining these two processes resulted in a collision risk, or as we redefine it, 'fatality risk'. Other studies also used these same variable sets (Jaarsma et al. 2007; Patrick et al. 2012; Girardet et al. 2015), however, Visintin et al. (2016), formally set up a conceptual framework for predictive road-kill models.

In this paper, we adopted a conceptually similar approach to predict road fatality risk on the Victoria road network (South-eastern Australia) using the Eastern Grey kangaroo (*Macropus giganteus*) as a case study species. However, we predicted crossing probability using a connectivity model that considered species occurrence probability and landscape resistance to movement. The likelihood of crossing a road depends on both the occurrence of a species at one side of the road and on the connectivity among habitats across roads. Thus, we expect that a connectivity metric could better predict crossing probability than species occurrence in the vicinity of the road – as applied by Visintin et al (2016). To obtain collision probability, we used an equation which considers traffic volume, a kill zone (road width) and the animal speed when crossing a road (Hels and Buchwald 2001; Jaarsma et al. 2006; Litvaitis and Tash 2008). We tested two approaches for this later process: the original exponential equation (higher traffic results in higher collision risk) and an adapted equation which includes an avoidance parameter which means that from a given traffic volume animals start to avoid crossing the road and collision risk decreases.

Methods

Study area and target species

The study area was the 227,819 square kilometer state of Victoria in south-east Australia and its road network. We considered only freeways, highways, and major arterial roads based on VicRoads classification (VicRoads 2017a) and divided the road network into 500 m segments (n = 47,730 segments). We used an Australian native species, the Eastern Grey kangaroo (*Macropus giganteus*), as the target species. Grey kangaroos are large mammals and road-kills are frequently reported on Victorian roads (Visintin et al. 2016). Given their large body size, there is a human safety concern (Abu-zidan et al. 2002; Klöcker et al. 2006).

Crossing probability

We used a land cover map with a pixel resolution of 100m and nine cover classes: exotic largely treeless, native woody cover, exotic tree cover (urban trees), exotic plantation forestry, native grasslands and shrublands, native sparse cover (other native cover and bare ground), native open, non-woody wetlands and waterbodies, artificial impoundments, and exotic potential plantation trees (Newell et al. 2006). We elicited two experts on kangaroo ecology to provide resistance values to kangaroo movement for each land cover class. We combined their responses using an analytic hierarchy process (Saaty 1987; Hurley et al. 2009) by which experts make decisions using a series of pairwise comparisons among classes (see details in Appendix A). We verified the consistency of experts' evaluation with a ratio between the Consistency Index and the Random Index of less than 0.1, which means that values for each class were consistent between experts (Saaty 1987). We tested three thresholds of relative likelihood of grey kangaroo occurrence from Visintin et al. (2016) to serve as source areas for the connectivity maps: only patches with more than 0.5 (n = 373), 0.7 (n = 164) or 0.8 (n = 65) relative likelihood of occurrence (Appendix B).

We developed the connectivity maps using circuit-theory in Gflow software (Leonard et al. 2017). Circuit theory-based connectivity is modelled by assigning a resistance value – indicating the degree of permeability – to each pixel in a landscape matrix for electron flow (or animals by analogy). Landscapes are represented as conductive surfaces, with low resistances assigned to landscape feature types that are most permeable to movement, and high resistances assigned to movement barriers (McRae et al. 2013). We used different criteria for convergence factor (1N and 4N; Leonard et al. 2017), that is, a correlation factor of the current density between pairs of source areas (it defines the number of decimal places for the correlation threshold among intermediate connectivity maps; 1N corresponds to 0.9 and 4N correspond to 0.9999). The output map for each criterion was a summation of per-cell current density (in amperes) for all source pairwise nodes. We re-scaled the current density values to be from 0 to 1 and sampled the mean current density in all intersecting grid cells for each 500 m road segment as the crossing probability. We obtained six connectivity maps based on the previous criteria (Table 1). For class 0.5 of species occurrence, we retained only one result, because for convergence factors 1N and 4N the connectivity maps were highly correlated (> 0.95). In the final risk models, we only used the map with the best road-kill predictive performance (based on validation).

Collision probability

To obtain collision probability for each 500m road segment, we used the traffic volume, animal speed, and road width following Hels and Buchwald (2001) and Jaarsma et al. (2006) equation: 1-exp(-N*(a/v), where N is traffic volume; “a” is a kill zone (road width), and “v” is animal speed. We refer to this model as collision probability 1 (Co-1). We adapted the Hels and Buchwald (2001) equation to include an avoidance factor: 1-exp(-N*(a/v) * exp(- c*N), where N is traffic volume; “a” is a kill zone (road width), “v” is animal speed, and “c” is a parameter related to the traffic threshold of road avoidance. We selected our parameter “c” based on data from Visintin et al. (2017) which found the peak of collision rate for kangaroo species at 5.000 vehicles/day. We refer to this adapted model approach as collision probability 2 (Co-2).

We modeled traffic volume for each segment using the same approach as Visintin et al. (2016). Average annual daily traffic (AADT) counts were recorded on, and provided by, VicRoads for 2333 road segments in the year 2013. We regressed AADT on distance to developed land use (km), distance to freeways and highways (km), population density (individuals per km^2), road class and road density (km per km^2) using random forests (Breiman 2001). Using the model fit, we predicted traffic volume to all 47,730 road segments. Road widths were obtained from VicRoads (2017) and for Eastern Grey kangaroo road crossing speed, we used half of the fastest recorded speed for the genus *Macropus* which equals 333 m/min (Hirt et al. 2017).

Validation

We used 1,023 kangaroo road-kill recordings from reported incidents to the Wildlife Victoria organization between 2010 and 2014 (Wildlife Victoria 2015). We then fitted Binomial models to the data using the presence of observed road-kills on each segment.

We fitted three types of models: crossing models, collision models, and crossing and collision in the same model (bivariate). For the bivariate model, we selected the best crossing model among the six connectivity outcomes – based on its predictive performance – and the best collision model.

We cross-validated the models by randomly splitting the data into 10 folds (nine of these subsets for training the model and one for assessing model performance). We repeated this procedure 100 times for each model. We obtained ROC values to assess the model predictions. We also compared the Akaike information criterion (AIC) of each model. We performed these analyses using the *train* function in the *caret* package (Kuhn 2008) in the R environment (R Core Team 2017).

Results

Crossing probability

The Cr-0.7-4 model, which used connectivity maps generated from 0.7 species occurrence likelihood as source patches and 4N convergence factor (Figure 1), was the best predictive model for estimating kangaroo crossing probability (Table 1) and was selected for final modelling.

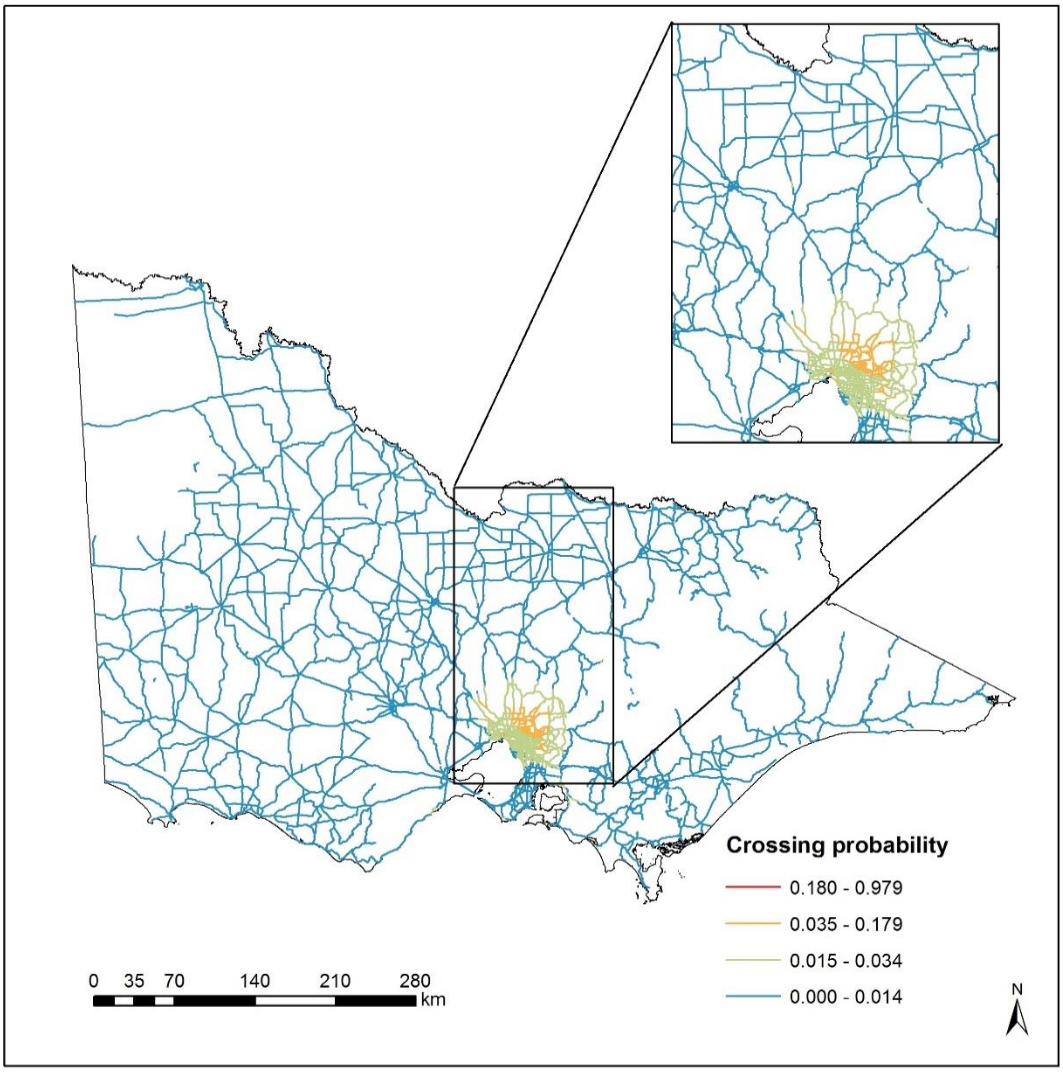


Figure 1: Eastern grey kangaroo road crossing probability map for the Victoria state road network based on a connectivity map generated from 0.7 species occurrence likelihood as source patches and 4N convergence factor.

Table 1: Crossing models acronyms, named according to species occurrence likelihood and convergence factor, and their predictive performance measured by Akaike Information Criteria (AIC) and Receiver Operator Characteristic (ROC). Highlighted model (in bold) was selected for the final models.

Model Acronym	Occurrence Likelihood threshold	Convergence Factor	AIC	ROC
Cr-0.5	0.5	1N/4N	9791	0.663
Cr-0.7-1	0.7	1N	9827	0.423
Cr-0.7-4	**0.7**	**4N**	**9582**	**0.692**
Cr-0.8-1	0.8	1N	9824	0.611
Cr-0.8-4	0.8	4N	10027	0.326

Collision probability

As expected, the Collision Probability 1 (Co-1) and Collision probability 2 (Co-2) models differed in their relationship to traffic volume (Figure 2). Collision probability 2 (AIC = 9632.6; ROC = 0.66; Figure 3) was a better predictor of eastern kangaroo fatalities than collision probability 1 (AIC = 9878.3; ROC = 0.65). We used Co-2 for final modelling (Figure 3).

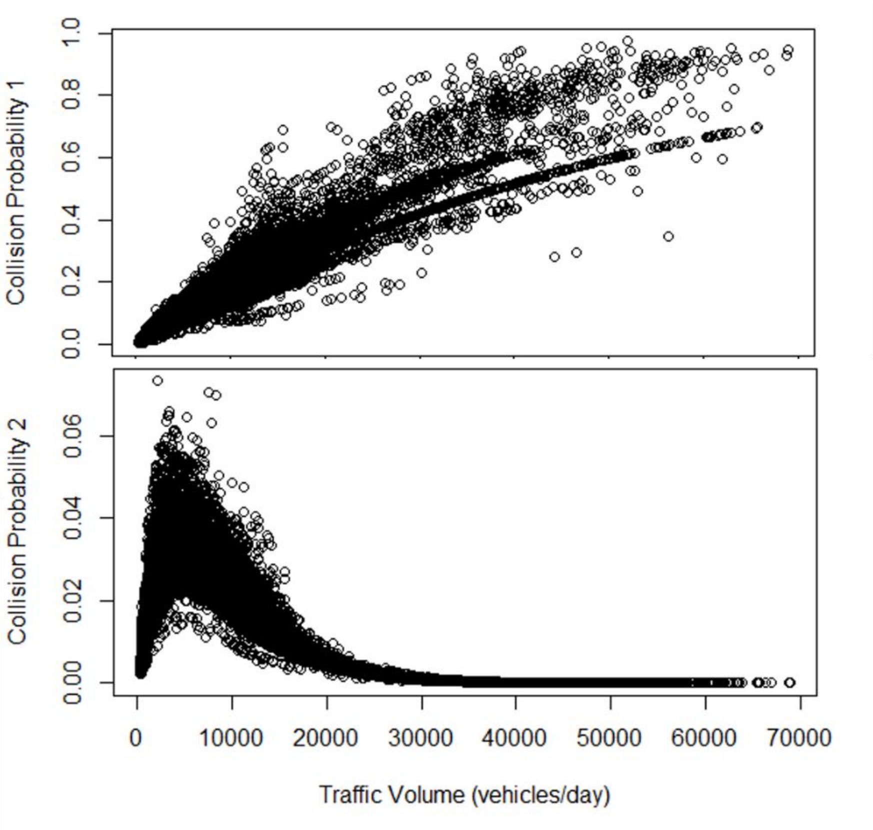


Figure 2: Relationship between Collision Probabilities 1 and 2 models and traffic volume for Eastern Grey kangaroos on each road segment (n = 47,730) of the Victoria state road network.

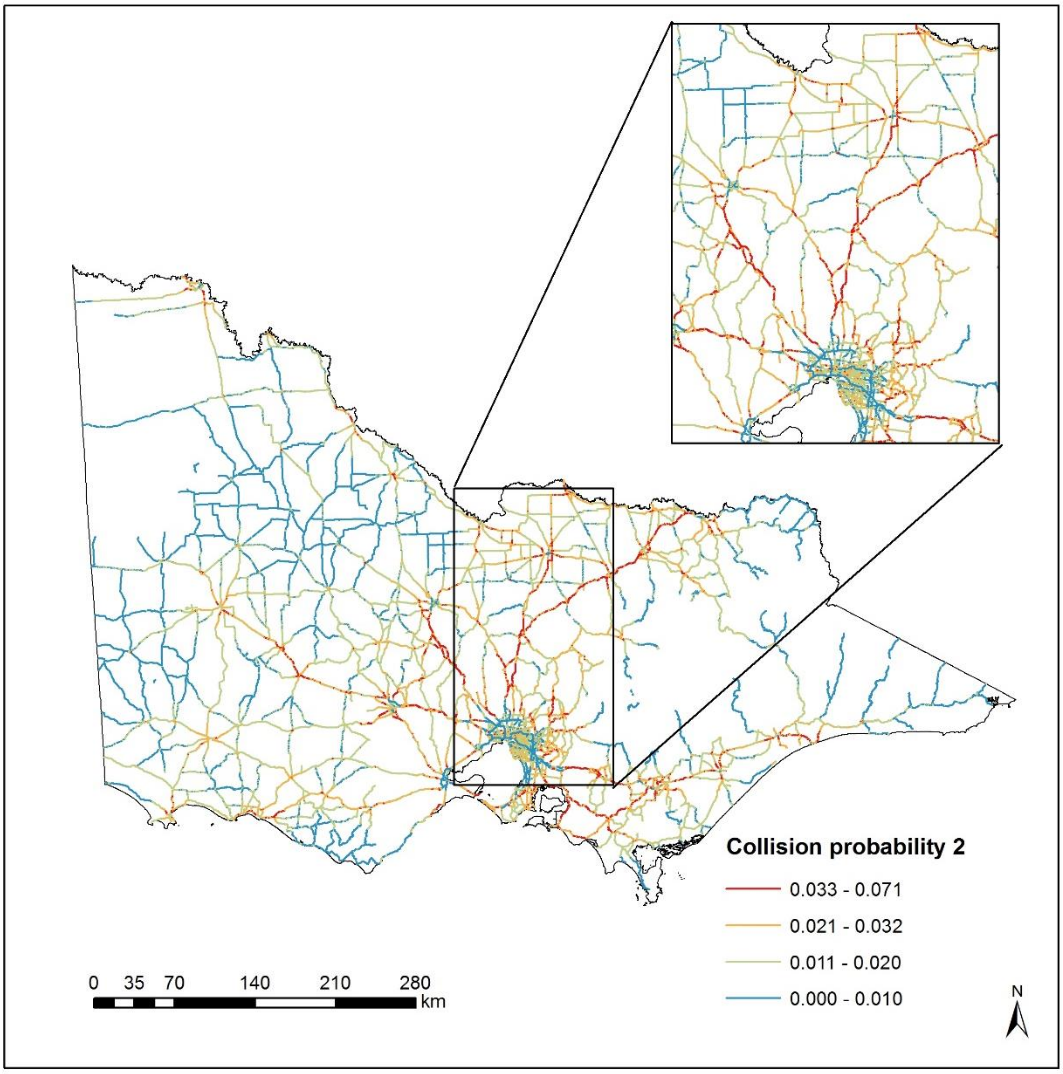


Figure 3: Eastern Grey kangaroo collision probability map based on the Co-2 model for the Victoria state road network.

Predictive performance

The bivariate Cr-07-4 + Co-2 Model, which considered crossing and collision probability 2, showed the best predictive performance when we compared all final models (Figure

4). It also had the lowest AIC (AIC = 9337) when we compared to Cr-07-4 model and Co-2 model separately. The resulting predicted fatality probability map of this model is presented on Figure 5.

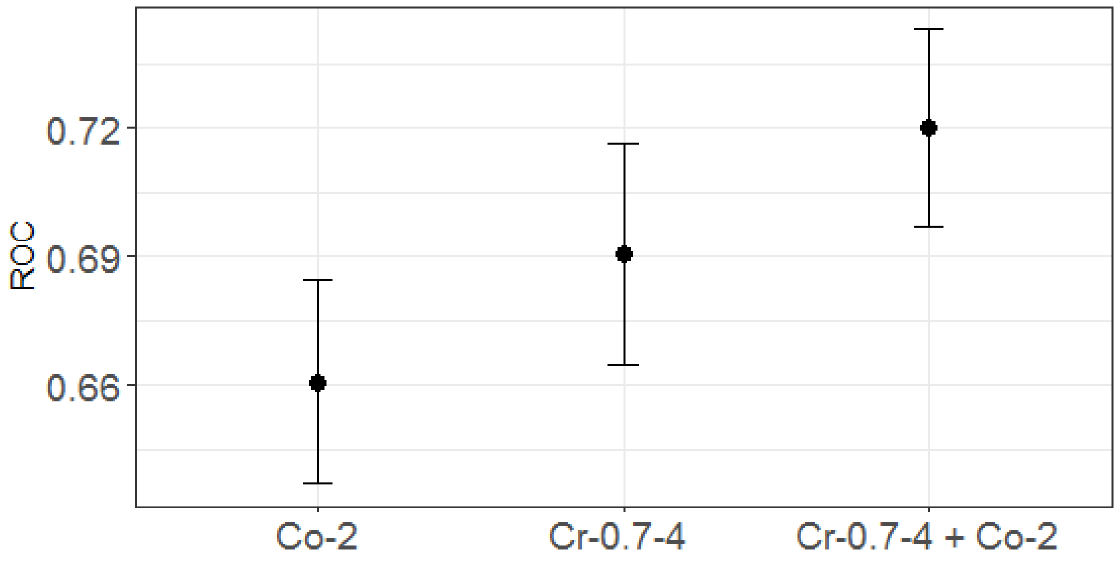


Figure 4: Predictive performance based on receiver operator characteristic (ROC) for Co-2 (Collision probability 2), Cr-0.7-4 (Crossing probability) and Cr-0.7-4+Co-2 (Crossing probability and Collision probability 2). The bars correspond to standard deviations.

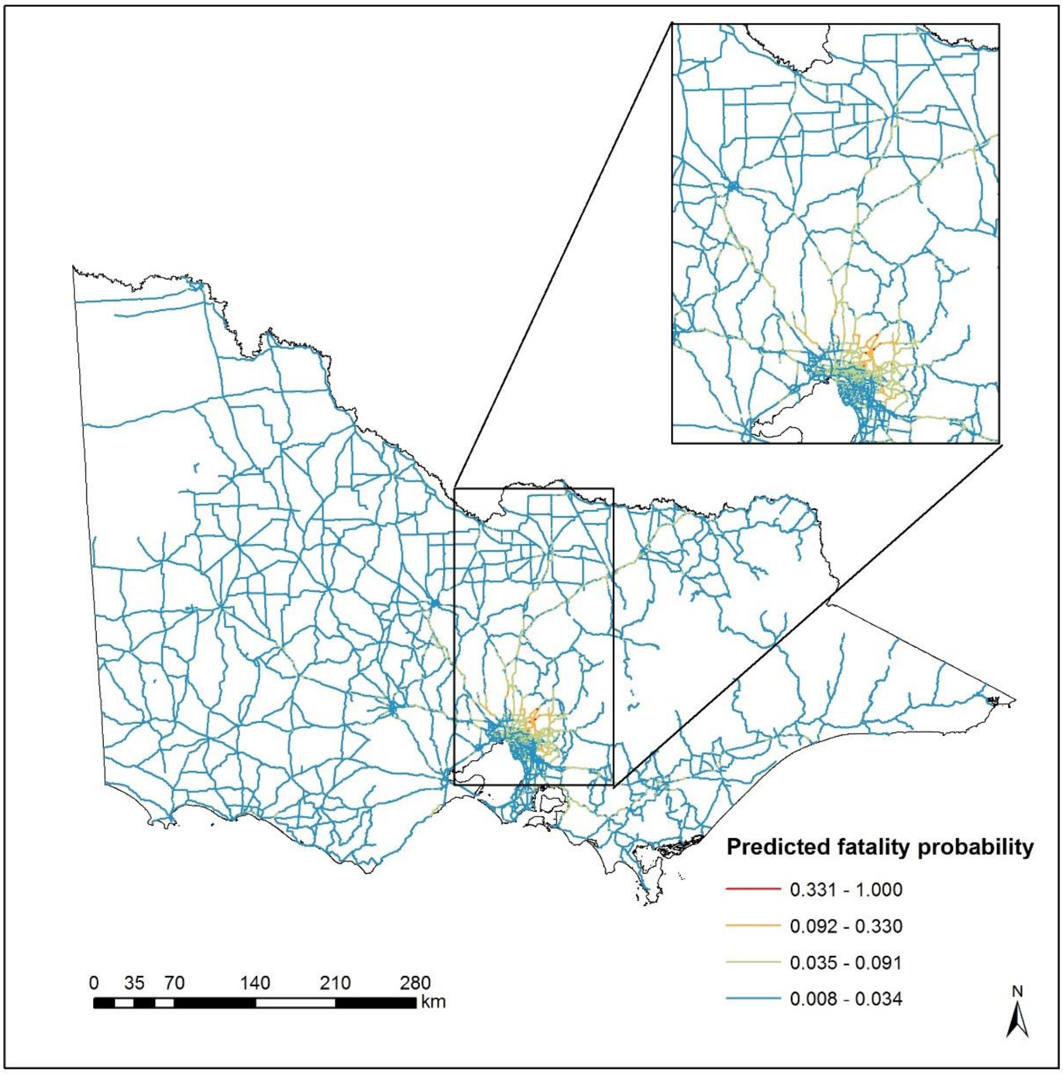


Figure 5: Predicted fatality probability of the Eastern Grey kangaroo on all road segments in Victoria state from the Cr-0.7-4+Co-2 model, which considered crossing probability and collision probability 2 in the same model.

Discussion

In this study we demonstrated that taking crossing probability and collision probability into account in an integrated model may provide better predictions of kangaroo road-kill risk than univariate models. Although we used the same framework as Visintin et al. (2016), considering crossing probability (exposure) and collision probability (hazard), and the same species and road network, our model had a lower predictive performance

(ROC = 0.72 versus ROC = 0.81). Both studies differ on the variables used to build each sub-model (occurrence likelihood versus connectivity maps to estimate crossing probability and traffic volume and vehicle speed versus traffic, road width, and animal speed to estimate collision probability). Apparently, the simpler model of Visintin et al. (2016) outperformed our model. However, our model may be more appropriate for researchers that have empirical movement data or good information about species movements. Furthermore, as road segmentation and road-kill sample for validation also differed among studies, only comparing models with all the possible combinations of sub-models building, in the same road system and with the same dataset, will allow us to select the best approach.

One apparent improvement of our approach is the adapted collision equation, which considered not only the traffic volume but also a species road avoidance parameter, resulting in a better collision probability model. Some previous studies found that an exponential distribution was not the best description for collision risk and traffic association (Gunson et al. 2011). Thurfjell et al. (2015) demonstrated that above a given traffic volume, animals start to avoid crossing and, thus, they are not hit by vehicles. We suggest that the use of the collision probability equation, in its original version (Hels and Buchwald 2001; Jaarsma et al. 2006), should be used with caution on roads or road networks with high traffic or traffic variation and other alternatives should be tested, with thresholds modeled that are unique to each species.

In our study we used a connectivity map to predict the crossing probability. This option is supported by Kang et al. (2016) who found that the effect of habitat connectivity on road-kill abundance was stronger for large mammal species than for small species. However, the ability of connectivity to explain road-kills is lower than local landscape variables and road characteristics (Girardet et al. 2015; Kang et al. 2016). Contradicting our initial expectation, the better overall predictive performance of the Visintin et al. (2016) model may result from their use of occurrence likelihood only, since kangaroo crossings and consequently road-kills may be more affected by local landscape variables than connectivity.

We have demonstrated an easily implemented landscape resistance assessment by expert's opinion. Whilst it had been used previously by Hurley et al. (2009) to predict moose-vehicle collisions, and touted as a valuable tool, some critics have depreciated this method (Clevenger et al. 2002). Connectivity maps could be improved with the use of more than one layer to define the landscape resistance values, as in Dutta et al. (2016), which considered transportation infrastructure. Although rarely available, telemetry data would strongly improve resistance estimates and connectivity maps (Proctor et al. 2015; Loraamm and Downs 2016) and movement simulations are another possible approach to improve these maps (Beier et al. 2008; Semeniuk et al. 2014). In contrast to Gonçalves et al. (2018), which applied the same general approach to obtain crossing probability for a single road, the crossing model outperformed the other collision models in our study. Here, we selected core areas by using species occurrence likelihood data. This performed better than selecting core areas using habitat preference based on expert opinion as done by Gonçalves et al (2018).

Visintin et al. (2016) propose their framework to be highly flexible and uses several modelling approaches and input data to build the sub-models. This largely depends on available information for each study area. Testing multiple approaches in a single study for multiple species would help compare the performance in each situation. At a network scale, and even at a road scale, combining solutions for multiple species is a challenge; however there have already been proposals in that direction (e.g. dispersal guild approach where species are grouped on similar behavior, see Lechner et al. 2017).

Few other studies also showed good performances for predicting road-kills using these two processes in a single model (Visintin et al. 2017; Nelli et al. 2018). Although we are not aware of any precedents using this kind of models to plan for mitigation installation, the accumulating evidence supports their use for this purpose in contexts where observations are not available or not attainable, like regional road networks.

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Supplementary material

Appendix A. Explanation for how we obtained the resistance value based on experts opinion and Analytic Hierarchy Process.

We used the Analytic Hierarchy Process to facilitate decision making about resistance values. Experts determined resistance values by a series of pairwise comparisons based on Saaty (1987).

Experts' responses varied from 1 to 9 and were based on the comparison between land use classes. The larger the score is, more resistant to kangaroo movement is that class:

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two classes contribute equally for the goal
3	Moderate importance of one over another	Experience and judgement slightly favour one class over another
5	Essential or strong importance	Experience and judgement strongly favor one class over another
7	Very strong importance	A class is strongly favoured and its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one class over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgements	When compromise is needed

Table below showed the nine classes of land use of Victoria state used in our land cover and use map obtained from Newell et al. (2006):

Cover Class Code	**Land Use**
A	Exotic - largely treeless (Not native vegetation or tree cover)
B	Native - woody cover (including heaths and woody wetlands)
C	Exotic - tree cover (Urban trees, windbreak trees and other exotic trees)
D	Plantation - tree cover (Plantation forestry (mainly Blue Gums and Pines)
E	Native - grasslands and chenopod shrublands (including some wetlands)
F	Native - sparse cover (Other native cover and bare ground (fires scars, sand dunes, very low cover on floodplains etc.)
G	Native - open, non-woody wetlands and waterbodies (Potential or existing non-woody wetland cover - includes smaller embayments and estuaries)
H	Artificial impoundment (Large artificial freshwater impoundments)
I	Exotic - tree cover (Potential plantation trees)

Two experts discussed their opinions and gave values for each class based on the pairwise comparison (one value per class). The value in each cell of the table below corresponds to the result of the pairwise comparison. All comparisons were always made between rows and columns in this order. For example, class G is five times more resistant than class A. Consequently, class A is five times less resistant than class G (1/5=0.20).

Land cover Code	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
A	1.00	1.00	1.00	0.50	1.00	0.33	0.20	0.14	0.50
B	1.00	1.00	1.00	1.00	1.00	0.50	0.25	0.14	1.00
C	1.00	1.00	1.00	1.00	1.00	0.50	0.25	0.14	1.00
D	2.00	1.00	1.00	1.00	1.00	0.50	0.25	0.14	1.00
E	1.00	1.00	1.00	1.00	1.00	0.50	0.50	0.14	1.00
F	3.00	2.00	2.00	2.00	2.00	1.00	1.00	0.14	1.00
G	5.00	4.00	4.00	4.00	2.00	1.00	1.00	0.25	1.00
H	7.00	7.00	7.00	7.00	7.00	7.00	4.00	1.00	1.00
I	2.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

On the next step, all cell values were divided by the sum of its specific column resulting in the table below:

Land cover Code	A	B	C	D	E	F	G	H	I
A	0.0435	0.0526	0.0526	0.0270	0.0588	0.0270	0.0237	0.0459	0.0588
B	0.0435	0.0526	0.0526	0.0541	0.0588	0.0406	0.0296	0.0459	0.1176
C	0.0435	0.0526	0.0526	0.0541	0.0588	0.0406	0.0296	0.0459	0.1176
D	0.0870	0.0526	0.0526	0.0541	0.0588	0.0406	0.0296	0.0459	0.1176
E	0.0435	0.0526	0.0526	0.0541	0.0588	0.0406	0.0592	0.0459	0.1176
F	0.1304	0.1053	0.1053	0.1081	0.1176	0.0811	0.1183	0.0459	0.1176
G	0.2174	0.2105	0.2105	0.2162	0.1176	0.0811	0.1183	0.0804	0.1176
H	0.3043	0.3684	0.3684	0.3784	0.4118	0.5677	0.4734	0.3215	0.1176
I	0.0870	0.0526	0.0526	0.0541	0.0588	0.0811	0.1183	0.3215	0.1176

Finally, we calculated the weight, lambda and relative weight (which corresponds to the used resistance value) following the equations indicated in the table below:

Land Cover Code	Sum of rows	Sum of columns	Weight (sum of rows/number of classes)	λ (weight/sum of columns)	Relative Weight (Resistances)
A	0.390	23	0.043	0.997	11.78
B	0.495	19	0.055	1.046	14.96
C	0.495	19	0.055	1.046	14.96
D	0.539	18.5	0.060	1.108	16.27
E	0.525	17	0.058	0.992	15.85
F	0.930	12.33	0.103	1.274	28.08
G	1.370	8.45	0.152	1.286	41.36
H	3.312	3.11	0.368	1.143	100
I	0.944	8.5	0.105	0.891	28.50

We checked the consistency between comparisons based on the equation $CI = (\sum \lambda\text{-}n)/(n\text{-}1)$ where "n" is the number of classes and "λ" is obtained from the table above. Our Consistency Index (CI) equals 0.0977.

To evaluate if the consistency is acceptable or not, we also calculated a Consistency Ratio as CR = CI/RI. The CR is obtained by comparing the CI with an average random consistency index (RI) (Saaty, 1987). If CR it is not lower than 0.10, experts must revise their judgments related to pairwise comparisons. The RI for nine variables is 1.45 (Saaty, 1987). We calculated the CR as 0.067 and, thus, we accepted and used the experts evaluation for each cover class resistance in the connectivity map.

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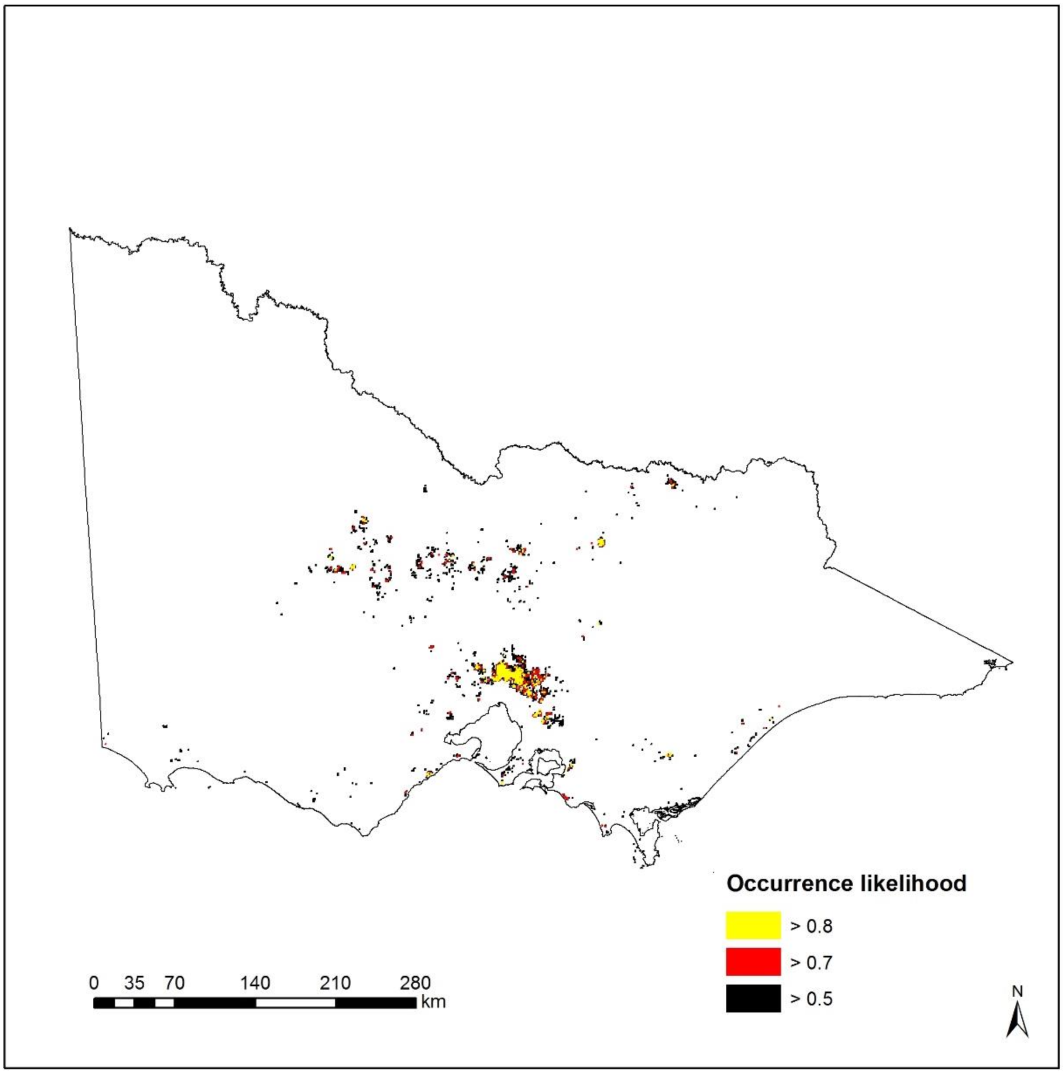
Appendix B. Source areas based on predicted relative likelihood of grey kangaroo presence. Black are areas with more than 0.5 of occurrence, red are areas with more than 0.7 of occurrence and yellow are areas with more than 0.8 of kangaroo occurrence. These data are based on the occurrence likelihood of kangaroo estimated by Visintin et al. (2016). The larger likelihood thresholds are within the smaller ones.



Considerações finais

Nessa tese, explorei diferentes formas de identificar quais são os locais com maior incidência de atropelamentos e poder, com isso, indicar locais prioritários para implementação de medidas de mitigação. Com os resultados do primeiro capítulo, concluí que os atropelamentos de fauna podem ser muito numerosos em determinados contextos, neste caso, para os répteis na BR-101, no qual estimei que mais de 15 mil répteis podem morrer atropelados por ano em 277 km. Além disso, mostrei que é possível identificar locais de maior agregação e que se eles tivessem uma mitigação 100% efetiva poderiam evitar 45% dos atropelamentos encontrados. Nesse capítulo exemplifiquei como é importante levar em consideração os erros de amostragem na estimativa da fatalidade, bem como ilustrei como a identificação das zonas de agregação de fatalidades pode otimizar o esforço de mitigação. Além disso, evidenciei a importância do estudo dos atropelamentos em répteis que ainda é um grupo negligenciado em trabalhos de ecologia de estradas e apresentei atributos da paisagem que podem estar associados aos trechos de maior número de fatalidades.

O segundo e terceiro capítulos dessa tese apresentaram uma abordagem preditiva para identificar locais que seriam prioritários para mitigação do impacto de atropelamento de fauna. Explorei nesses modelos os dois processos associados à ocorrência de fatalidades em uma estrada: a probabilidade de travessia do animal e de colisão com um veículo. Com o segundo capítulo, conclui que é possível usar dados de tráfego de veículos e tamanho e velocidade dos animais para predizer locais de maior concentração de atropelamentos, entretanto deve se ter cuidado pois a performance dos modelos variou com a espécie. Essa abordagem pode ser utilizada em um contexto de construção de novas estradas ou de pavimentação de estradas existentes, para as quais é possível modelar o futuro tráfego e avaliar a conectividade da paisagem para espécies de especial interesse.

Contudo, ainda são necessárias avaliações multiespecíficas, pois principalmente em países megadiversos, são raras as situações nas quais a proposição de medidas de mitigação é justificável apenas em uma espécie.

Para o contexto de rede de estradas, concluí a partir do capítulo 3 que é possível predizer o atropelamento utilizando a probabilidade de travessia e a probabilidade de colisão em um mesmo modelo. Demonstrei ainda que a equação adotada pela maioria dos autores para calcular a probabilidade de colisão precisa ser utilizada com cautela, pois nem sempre a relação entre o risco de atropelamento e o tráfego é exponencial. O modelo proposto no terceiro capítulo da tese é apropriado, por exemplo, para o contexto do Programa de Rodovias Federais Ambientalmente Sustentáveis (Portaria Interministerial n° 288, de 16 de julho de 2013), que prevê que rodovias construídas anteriormente à exigência de licenciamento ambiental passem por um processo de regularização dentro de um período de 06 a 20 anos. Espera-se que o impacto de 55.000 quilômetros de estradas seja avaliado, com a proposição de medidas mitigadoras relacionadas especialmente à diminuição da mortalidade e aumento da permeabilidade da paisagem para a fauna. Desconheço o andamento da implantação do processo de regularização ambiental demandado pela portaria, mas é notório que nessa escala a geração de dados observacionais de fatalidades é extremamente onerosa. Assim, considerando as limitações de recursos para estudos de monitoramento da mortalidade e extrema complexidade de executá-los nessa abrangência, acredito que os modelos propostos no terceiro capítulo podem ser úteis não só para identificar locais prioritários para mitigação, mas também para indicar locais importantes para focar os estudos que queiram avaliar localmente este impacto, explorando efeitos populacionais, por exemplo.

Portanto, concluo que os resultados aqui apresentados podem auxiliar na identificação de locais para possível implementação de medidas de mitigação dos atropelamentos de fauna. Além de servirem para ajudar na identificação de áreas prioritárias para execução de estudos locais de fatalidade em rodovias. Ainda é necessário explorar outras maneiras de calcular e integrar as probabilidades utilizadas nesta tese, tanto a probabilidade de travessia quanto a de colisão. Entretanto, demonstrei aqui uma forma possível de predizer atropelamentos para um contexto em que não há dados dessa natureza disponíveis, seja para estradas novas ou para uma rede de estradas. A utilização de modelos preditivos é uma abordagem ainda pouco usada e aplicada no Brasil, mas muito urgente e necessária para a conservação da natureza de uma forma menos onerosa e mais rápida.

Para além dos artigos que compõem esta tese, queria também utilizar essas considerações finais para dizer o que concluo desses quatro anos e três meses de doutorado no Programa de Pós-Graduação em Ecologia da Universidade Federal do Rio Grande do Sul. Acredito que o período de doutorado pra mim foi muito além destas páginas aqui escritas e que não têm espaço para descrição em nenhuma seção. Além dos artigos aqui apresentados, alcancei objetivos importantes pra minha formação: orientei e participei de outros trabalhos acadêmicos (FREITAS et al., 2017), fiz divulgação científica, que considero uma atividade bastante importante e pouco valorizada (GONÇALVES, 2015; KINDEL et al., 2017a; colunas Fauna e Estradas em www.faunanews.com.br), participei de cursos para capacitação de profissionais na área de Ecologia de Estradas e de atividades diretamente ligadas às políticas públicas para o setor de transportes, as quais também resultaram em trabalhos acadêmicos (KINDEL et al., 2017b). Consegui mesmo com a atual situação do nosso país, ter uma experiência acadêmica fora do país que foi extremamente enriquecedora tanto profissional quanto pessoalmente. Com certeza, todas essas experiências fortaleceram a minha formação como aluna e pesquisadora.

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