Received: 25 January 2022 | Revised: 31 January 2023 | Accepted: 9 February 2023
DOI: 10.1111/aec.13295

RESEARCH ARTICLE

Prioritizing road mitigation using ecologically based land-use planning

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Funding information
Conselho Nacional de Pesquisa e Desenvolvimento Científico e Tecnológico (CNPq), Grant/Award Number: 308632/2018-4; Foundation Segre; Fundação para a Ciência e Tecnologia, Grant/Award Number: CEECIND/03265/2017; Nashville Zoo; Royal Zoological Society of Scotland

Abstract
Wildlife–vehicle collisions (WVCs) are a critical threat to biodiversity and human safety. To implement WVC mitigation measures where most needed, we need to link models predicting the probability of the presence of species, at large spatial scales, with the likelihood of occurring collisions along roads. Here, we propose a framework for the prioritization of road sections for implementing mitigation measures using ecologically based information. Within this framework, we first model the likelihood of WVC occurrence for focal species in road vicinity areas. We then use spatial prioritization tools to select road sections that entail a higher probability of WVC across the focal species using user-defined criteria for weighting species records. We applied this framework to Mato Grosso do Sul state (Brazil), using systematic information on WVC collected over 3 years along ca. 2000 km of roads. We focused on the WVC involving three large mammals commonly road-killed therein, which represent a threat to humans when involved in WVC: the lowland tapir *Tapirus terrestris*, giant anteater *Myrmecophaga tridactyla* and capybara *Hydrochoerus hydrochaeris*. We were able to identify road sections (<10% of the road network) that should be prioritized for implementing mitigation actions, which could significantly reduce the number of WVCs. However, the large extent of the road network classified as a priority for mitigation suggests the need to engage the public and private sectors in the early stages of the decision-making process, in order to reach a consensus on the prioritization. Our framework may improve the environmental licensing process, namely by guiding where mitigation measures should be implemented first.

KEYWORDS
large mammals, mitigation, spatial prioritization, species distribution modelling, wildlife–vehicle collisions

INTRODUCTION

Roads are the most ubiquitous infrastructure throughout the globe and are recognized as fundamental for human development and poverty alleviation (Cook et al., 2005; Dulac, 2013). However, they also pose serious threats to biodiversity (Coffin, 2007; Forman & Alexander, 1998; Van Der Ree et al., 2015). In fact, roads may represent barriers to animal movement, restricting their daily and dispersal movements and impeding access to key resources, leading to the loss of genetic variation (Forman & Alexander, 1998; Trombulak & Frissell, 2000; Desbiez et al., 2020; Barragán-Ruiz et al., 2021). Moreover, wildlife–vehicle collisions (WVC) represent a serious threat to wildlife populations (Barrientos et al., 2021; Rytwinski & Fahrig, 2012). For example, it has been estimated that over 8 million birds and 2 million mammals could be killed per year on Brazilian roads (González-Suárez et al., 2018). Such added mortality may reduce significantly the persistence of wildlife population in road vicinity areas (Ascensão & Desbiez, 2022). However, WVC also affects human safety, potentially leading to serious injuries or even death of people (Huijser, 2007; Conover, 2019). Furthermore, WVC entails a high financial cost, for example medical care, vehicle damage repair and traffic delays (Abra et al., 2019; Ascensão et al., 2021). Hence, understanding, assessing and predicting the spatial patterns of WVC is critical for biodiversity conservation, human safety as well as for a sustainable coexistence between human development and wildlife.

Roadkill surveys providing systematic WVC records can play an important role in helping to detect where WVC are most likely to occur (Ramp et al., 2005; Ascensão et al., 2017; Filius et al., 2020). Nevertheless, surveying the whole extension of the road network is not feasible due to financial and/or time constraints. On the other hand, WVC concentrations, or hotspots of mortality, may not always indicate where mitigation is most required, for example if the animal population is already depleted due to roadkill by the time the surveys start (Ascensão et al., 2019; Teixeira et al., 2017). Therefore, tools to predict where WVC risk is higher may improve the mitigation planning process by maximizing resource allocation and their potential benefits (Gunson & Teixeira, 2015).

WVC occur when individuals attempt and fail (collision) to cross a road. WVC tend to be concentrated in areas of higher animal abundance (Frangini et al., 2022; Fabrizio et al., 2019), but information on species abundance may be difficult to obtain (Ascensão et al., 2017, 2014; D'Amico et al., 2015). Yet, as the probability of species presence is known to be monotonically related to WVC rate (D'Amico et al., 2015; Visintin et al., 2016), modelling species presence using WVC data may provide important information on where focal species are likely to be more/less abundant in road vicinity areas (Garrote et al., 2018; Lin et al., 2019; Wright et al., 2020). Moreover, as different species are impacted by roadkill, some of which represent a serious threat to humans, accounting for multiple species presence can help to best determine which road sections should be mitigated first (Lin et al., 2019). Spatial prioritization analysis (Wilson et al., 2009; Moilanen et al., 2011; Toivonen et al., 2021) can be a valuable tool to identify those sites where the risk of WVC is highest, particularly when considering multiple species. Spatial prioritization can therefore assist the decision-making process, maximizing the cost–benefit relation of investment in mitigation measures and obtaining a significant reduction of WVC while improving road safety.

In this study, we propose a framework for the prioritization of road sections where mitigation measures should be considered first. Within this framework, we first model the likelihood of occurring WVC for different focal species using land cover predictors. We assumed that the likelihood of occurring collisions is interrelated with the probability of a species being present in road vicinity areas with that species. We then use spatial prioritization to select road sections that have a higher probability of WVC across the focal species. We applied this framework to Mato Grosso do Sul state (Brazil), using systematic information on WVC collected over 3 years along ca. 2000 km of roads. We focused on three large mammals commonly road-killed, that also representing a threat to humans when involved in WVC: lowland tapir (*Tapirus terrestris*), giant anteater (*Myrmecophaga tridactyla*) and capybara (*Hydrochoerus hydrochaeris*). The lowland tapir and the giant anteater are both considered vulnerable to extinction (IUCN, 2020), and together with the capybaras suffer from high rates of vehicle collisions in Mato Grosso do Sul (Ascensão et al. 2021b).

METHODS

Study area

The study was conducted in the state of Mato Grosso do Sul (MS), Brazil (Figure 1). The land cover is predominantly composed of fragmented forest patches (native vegetation) embedded in a matrix dominated by pasture, agriculture and (to a much less extent) production forest (*Eucalyptus* sp.). The climate is wet from October to March and dry from April to September, with mild year-round temperatures (range 21–32°C) (Alvares et al., 2013). The road network in MS comprises more than 19 000 km, of which ca. 50% is paved. Information about current WVC mitigation measures (e.g. fencing) across the state is not available.

WVC information

WVC records of focal species were obtained from the Anteaters & Highways Project (www.giantanteater.org) and from a private enterprise responsible for road maintenance (both databases had no spatial overlap). In the Anteaters & Highways Project, the data collection consisted of surveys performed by car (40–60 km/h speed) every 2 weeks, between February 2017 and February 2020, throughout six different transects on four roads, namely the federal roads BR-262 and BR-267, and the state roads MS-040 and MS-338, totalling 1158 km (Figure 1). The data collection by the private enterprise was performed by maintenance personnel along 847 km who regularly travelled the road for inspection, at a variable speed, on an hourly basis, between January 2017 and March 2020. All roads have two lanes

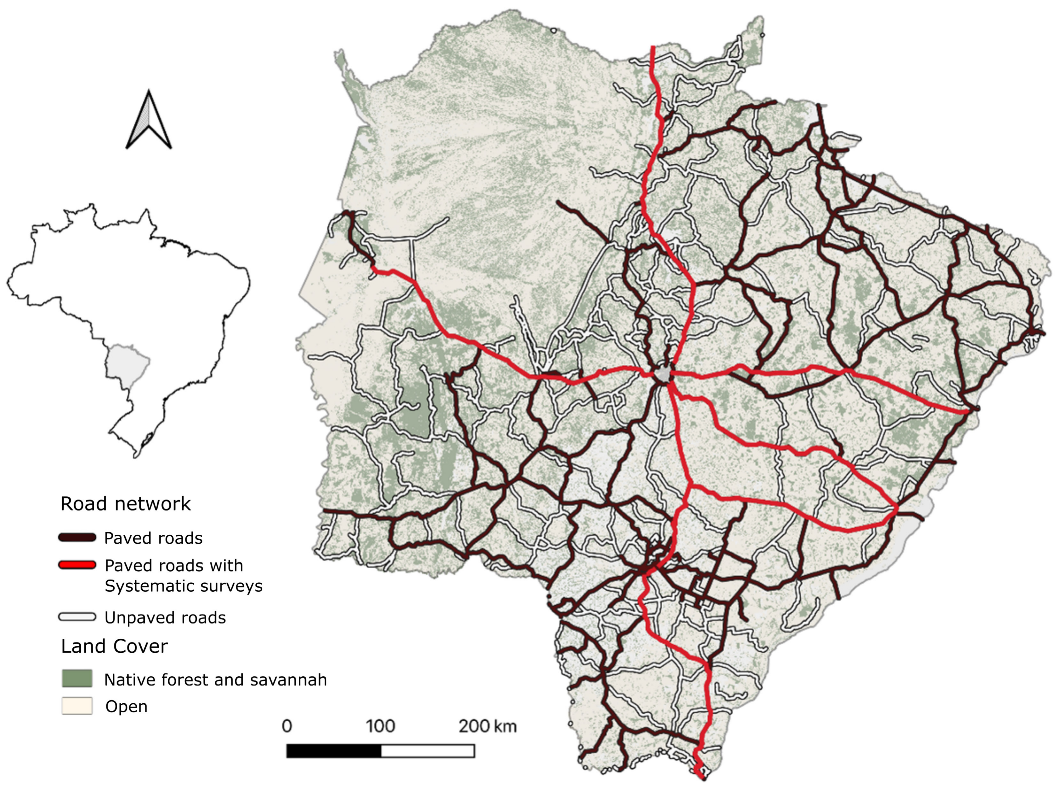

FIGURE 1 Mato Grosso do Sul state location in Brazil (inset) and its road network system. Green areas are native vegetation patches, predominantly forested areas including natural non-forested formations. Open areas include agricultural and human-modified areas.

and are paved. The location of all WVC was obtained using handheld GPS (spatial error < 10 m). In total, we assembled 2159 WVC records, including 425 of lowland tapir, 766 of giant anteater and 968 of capybara.

Environmental predictors

We collected information on eight environmental predictors (Table 1). All variables had a spatial resolution of 30 m. Terrain slope, altitude and terrain horizontal curvature were derived from a digital elevation model (Valeriano et al., 2009). The distribution of water on land, including areas not usually included in common water body shapes, was obtained from the terrain's horizontal curvature layer. Distance between the drainage network and the density of the drainage network was derived from IBGE hydrology data (1:250000; IBGE 2017). Land use was obtained from MapBiomas (Projeto MapBiomas 2019) which we aggregated into eight classes, namely 'agriculture and pasture', 'forest and savannah formation', 'natural non-forest formation', 'non-vegetated areas', 'silviculture', 'urban areas', 'water bodies'

TABLE 1 Environmental predictors available for modelling the like. All layers had a 30 m spatial resolution. Species: C – capybara; LT – lowland tapir; GA – giant anteater.

Predictor	Description	Year	Source	Species	Expected relationship between predictors and WVC data
Slope	Terrain slope (derived from the Digital Elevation Model)	2009	1	All	High relationship for all species likelihood of WVC occuring in vicinity areas.
Altitude	Altitude (derived from the Digital Elevation Model)	2009	1	All	High relationship for lowland tapirs' likelihood of WVC occuring in vicinity areas.
Curvature	Terrain horizontal curvature (derived from the Digital Elevation Model)	2009	1	C	High relationship for capybaras' likelihood of WVC occuring in vicinity areas.
Distance to the drainage network	Distance until drainage net using the IBGE files	2017	2	LT, GA	High relationship for all species likelihood of WVC occuring in vicinity areas.
Density to the drainage network	Density until drainage net using the IBGE files	2017	2	C	High relationship for capybaras' presence in vicinity areas.
Land use	Land-use classification for MS includes the following categories: agriculture and pasture, forest and savannah formation, natural non-forest formation, non-vegetated areas, other uses, silviculture, urban areas and water bodies.	2019	3	All	We expected categories related to natural formation to have a high relationship with all species likelihood of WVC occuring in vicinity areas.
Pasture	Percentage of pasture. Derived from the class 'pasture', MapBiomasv3.1 using the *Focal Statistics* tool (ArcGis 10.3) with a 33 × 33-pixel movie window.	2019	3	All	We expected areas with a high percentage of pasture formation to have an inverse relationship with species likelihood of WVC occuring in vicinity areas.
Forest	Percentage of forest and savannah. Derived from the classes 'forest and savannah formations', MapBiomasv3.1 using the *Focal Statistics* tool (ArcGis 10.3) with a 33 × 33-pixel movie window.	2019	3	All	We expected areas with a high percentage of forest to have a high relationship with all species likelihood of WVC occuring in vicinity areas.

Note: 1—www.webmapit.com.br/inpe/topodata/ (Valeriano et al. 2009).

2—https://www.ibge.gov.br/geociencias-novoportal/cartas-e-mapas/bases-cartograficas-continuas/15759-brasil.html?=&t=downloads.

3—Map Biomas Project (Collection 4.1, mapbiomas.org).

and 'others'. From this layer, we further derived the proportion of pasture and the proportion of forest and savannah vegetation.

We choose these predictors to model the likelihood of WVC occurring throughout the year (not accounting for seasonal variations), as our goal was to highlight candidate road sections for implementing static mitigation measures (road passages and fencing). Before the analysis, we screened for multicollinearity across variables using Pearson's correlation analysis, retaining uncorrelated ($r < |0.7|$) variables. Water density was highly correlated with water distance. For lowland tapir and giant anteater, we used water distance, while for capybara, we used water density, due to better responses obtained when comparing preliminary models.

Species models for WVC likelihood

The geographical region chosen for modelling species occurrence was the road vicinity area extending up to 2 km on each side of the road length sampled through monitoring. This distance was selected to ensure that we could capture enough variability of land cover information of road vicinity areas for modelling purposes, while also considering the home range areas of focal species: lowland tapir ca. 8 km^2, giant anteater ca. 4 km^2 and capybara <1 km^2 (Lowland Tapir Conservation Initiative, Anteaters & Highways Project data, Lopes et al., 2021).

In order to model the likelihood of occurring WVC, we used the maximum entropy algorithm (Phillips et al., 2006, 2017) as implemented in the MAXENT software (version 3.4.3; Phillips et al., 2017). The maximum entropy is a widely used algorithm and presented satisfactory results in recent works with similar objectives (Elith et al., 2011; Phillips et al., 2017). Maxent uses the maximum entropy algorithm to estimate the geographic range of a certain species intending geographical uniformity using environmental features as constraints (Phillips et al., 2017). The algorithm is also well known for requiring presence-background data or presence-only data as the species input. In our case, the use of presence-background data is adequate for our final prioritization (Phillips et al., 2006; Guillera-Arroita et al., 2015).

Because WVCs tend to be clustered, if we used the full data set of WVC, it could introduce biased information in the distribution models (Boria et al., 2014; Radosavljevic & Anderson, 2014). Specifically,0 in our case, two different databases and data collection could also include bias to the final models. Hence, before modelling procedures, we performed a spatial rarefaction to ensure the spatial independence of presence data (Araujo & Guisan, 2006). Rarefaction reduces the number of records by eliminating those falling under a pre-defined distance; the decision of the distance is generally made based on the species ecological features (Araujo & Guisan, 2006). Species' home ranges diameter was used as the filtering distance. Filtered records have no biased environmental information, preventing unrealistic outputs, including the inflation of roadkill risk on road sections. Rarefaction procedures were performed using the SDM toolbox (Brown, 2014) in ArcGIS 10.3 (ESRI 2015). After the rarefaction procedure, we were left with 134 records of the lowland tapir, 232 of giant anteater and 312 of capybara. We used this filtered data of WVC as the input information on MAXENT. We considered the geographic region pre-defined from the road vicinity areas as the pseudo-absences zone.

Model evaluation was performed using the bootstrap method of replicates (n = 100) with 70% of points for training and 30% for testing. Other settings included using 10000 background points, a convergence threshold of 10–5, 500 maximum iterations and a 'cloglog' output format. Model performance was assessed by the Area Under the Curve (AUC) (Fielding & Bell, 1997). Model predictions were made for the entire road network of MS, including unpaved roads. We choose to include unpaved roads so we could prioritize segments that will be most likely paved in the future and may require implementing WVC mitigation measures. We considered the prediction maps as reflecting the likelihood of occurring WVC.

For each species, the areas with WVC likelihood >0.75 were considered areas of high risk of WVC. This information was then used as input for spatial prioritization.

Road prioritization

The goal of using spatial prioritization was to help ranking and prioritize the road sections according to the likelihood of WVC occurrence for the three species. We performed the ranking using two criteria. At first, we assumed that while any collision involving the three focal species can be problematic, the larger the animal the more dangerous to humans the collision becomes. Hence, we weighed the three species in the prioritization according to their relative body mass, that is we gave the score = 1 for the giant anteater (mean body mass = ca. 32 kg), followed by capybara with score = 2 (mean body mass = ca. 48 kg), and tapir with score = 6 (mean body mass = ca. 166 kg). As second criteria, we ranked roads weighing species based on their conservation status. We wanted to check if conservation priorities have significant differences with this approach (see Appendix S1). The scores attributed for each species were 3 for the giant anteater and the lowland tapir and 1 for capybara.

We ran the spatial prioritization (1 km resolution due to Zonation restrictions) in two different analyses, separating paved roads from unpaved roads to obtain priority segments for each road type. Each road type will require specific mitigation measures and for unpaved roads measures could be recommended prior to licensing their pavement. Spatial prioritization was carried out within the ZONATION software using the 'additional benefit removal' rule (Moilanen, 2007; Di Minin et al., 2014). All other parameters were used with their default values (Lehtomäki & Moilanen, 2013; Moilanen et al., 2014).

For each road network (paved and unpaved), we considered the road sections classified within the top 10% of the ranking as being the priority candidate sections for the implementation of mitigation measures.

RESULTS

Species models for WVC likelihood

The WVC models for the three species presented a good performance (AUC = 0.79 ± 0.01 for lowland tapir, AUC = 0.72 ± 0.03 for giant anteater and AUC = 0.76 ± 0.01 for capybara). The most important variables explaining the lowland tapir WVC distribution were land use (relative importance: 32%) and proportion of pasture (29%). The probability of occurring WVC with lowland tapir was higher near urban areas and in areas dominated by agriculture and pasture. The most important variables explaining the WVC distribution of giant anteaters were the proportion of pasture (43%) and land use (22%). The probability of presence ranged between 0.50 and 0.75 when the proportion of pasture was higher than 0.40. The most important variables explaining the WVC distribution of capybara were land use (34%) and the proportion of forest and savannah vegetation (22%). The probability of the presence of capybaras was higher than 0.75 in natural forest formations and near urban areas (Figure 2).

The length of high-risk road sections (i.e. when the WVC likelihood >0.75) totalled 882 km for the lowland tapir, 1884 km for the giant anteater and 1676 km for the capybara (Figure 3). These lengths represent, respectively, 4%, 9% and 8% of the total road length of the MS state (Figure 3). High-risky areas for the lowland tapir were concentrated in the northeastern portion of the state, showing a more clustered pattern compared to the giant anteater and capybara. High-risky areas for giant anteater were identified across the whole state, that is it was not possible to identify a clear pattern in its distribution. High-risky areas for capybara were located near urban areas and in the Pantanal biome.

Spatial prioritization

The top 10% of paved and unpaved road sections highlighted by the prioritization process when using the criteria body mass were distributed across the state, with higher incidence along the BR-262 (ca. 102 km), BR-163 (ca. 100 km) and BR-267 (ca. 98 km) for paved roads, and higher incidence

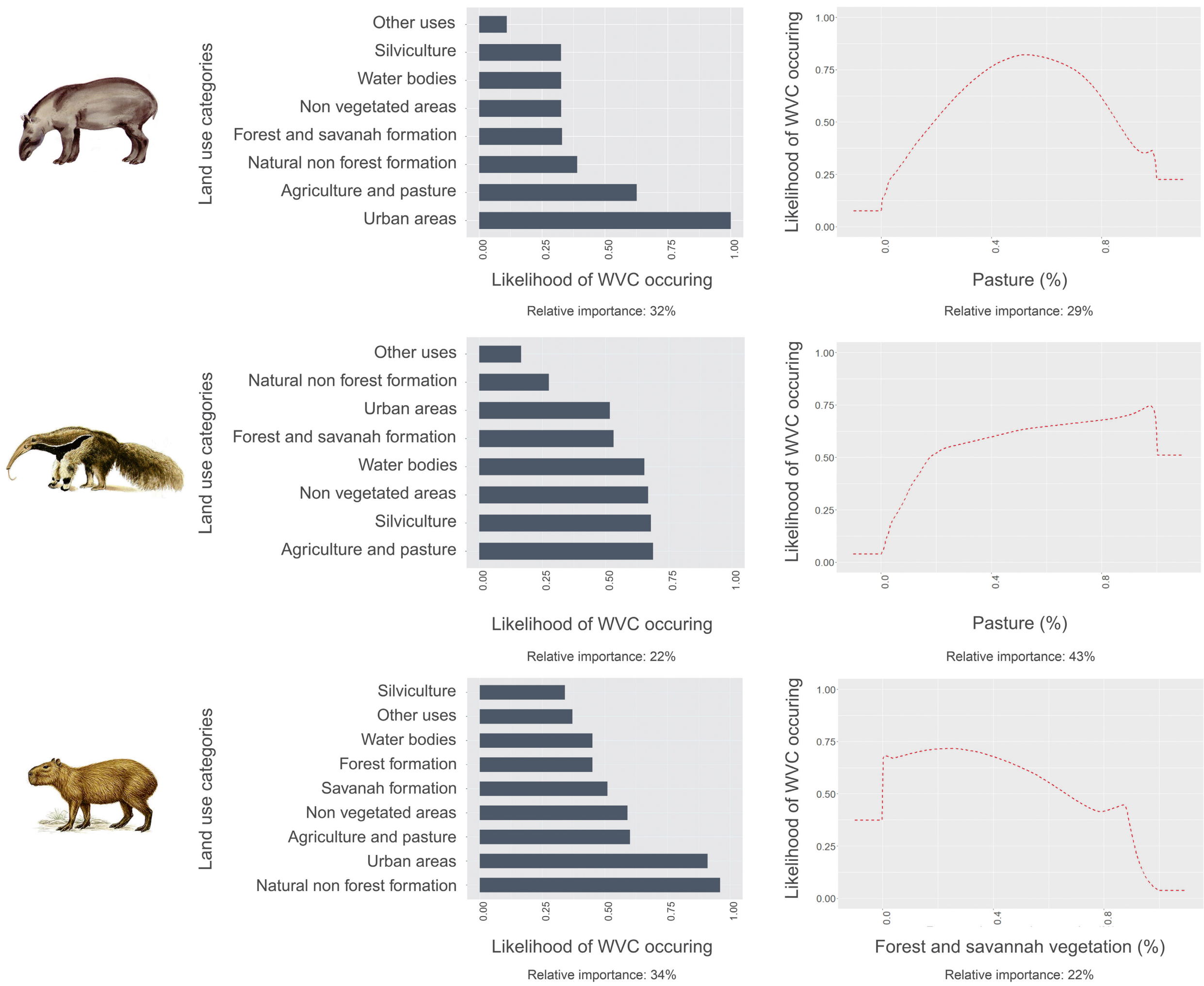

FIGURE 2 Response curves for all species models showing the two most important predictor variables for each species, organized by graph type. In order of importance: (1) lowland tapir: land use followed by percentage of pasture, (2) giant anteater: percentage of pasture followed by land use and (3) capybara: land use followed by the percentage of forest and savannah vegetation. For each predictor, the range for the likelihood of WVC predicted is also shown.

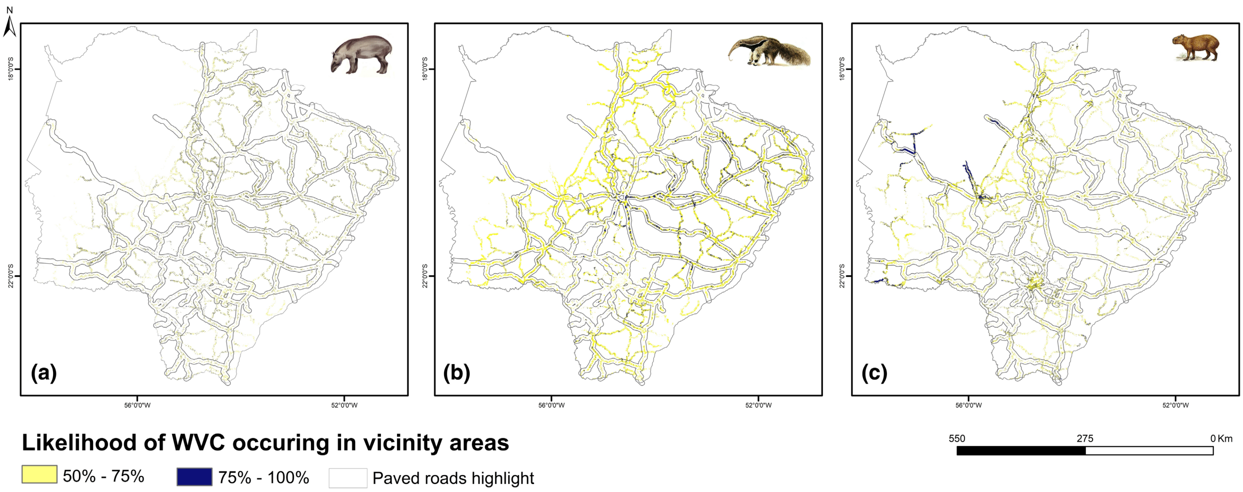

FIGURE 3 Likelihood of WVC occurring in vicinity areas, here considered a proxy of Wildlife–Vehicle Collision for the lowland tapir, giant anteater and capybara. Probability values were divided by quartiles. Paved were highlighted to distinguish them from unpaved segments.

along the MS-340 (ca. 76 km), MS-316 (ca. 55 km) and MS-142 (ca. 55 km) for unpaved roads (Figure 4). The pattern when using the second criteria (species conservation status) was very similar and therefore the results are shown in Appendix S2.

DISCUSSION

We integrated species distribution models with prioritization procedures to rank road sections according to their priority for the implementation of mitigation measures. Our analyses focused on three large mammals, the lowland tapir, giant anteater and capybara, across the Mato Grosso do Sul state, a huge territory where the road network is expanding at a fast pace and where road mortality seems to be a serious threat for biodiversity and human safety (Ascensão et al., 2017, 2021). According to our results, the most important predictors in the WVC probability models were similar for the three species (land use, proportion of forest and savannah and proportion of pasture), but the probability of occurring WVC varied across the study region, which is probably related to the species-specific ecological requirements. Unsurprisingly, the models of the three species indicated a broad distribution across the state, which is concordant with the distribution of WVC along most of the roads surveyed (Ascensão et al., 2017). The widespread distribution of these large mammals, and consequently of WVC, indicates that road mitigation measures must be planned and implemented throughout a large extension of the road network. This suggests the need to implement mitigation in hundreds or even thousands of kilometres of highways, which, however, represent less than 10% of the entire road network in the state.

In the prioritization process, we used two criteria, the first of which scores the risk to human lives and damage to vehicles. It was based on the likelihood of WVC occurrence and species' body mass. The rationale was that collisions with the largest species tend to cause higher damage to people and vehicles. It was possible to highlight road sections where WVC of the three focal species were more likely to occur. Such sections can be regarded as a priority for mitigation and where the cost–benefit of mitigation efforts are most likely to be maximized i.e., implementing them in road sections with the highest probability of occurring WVC allows a faster

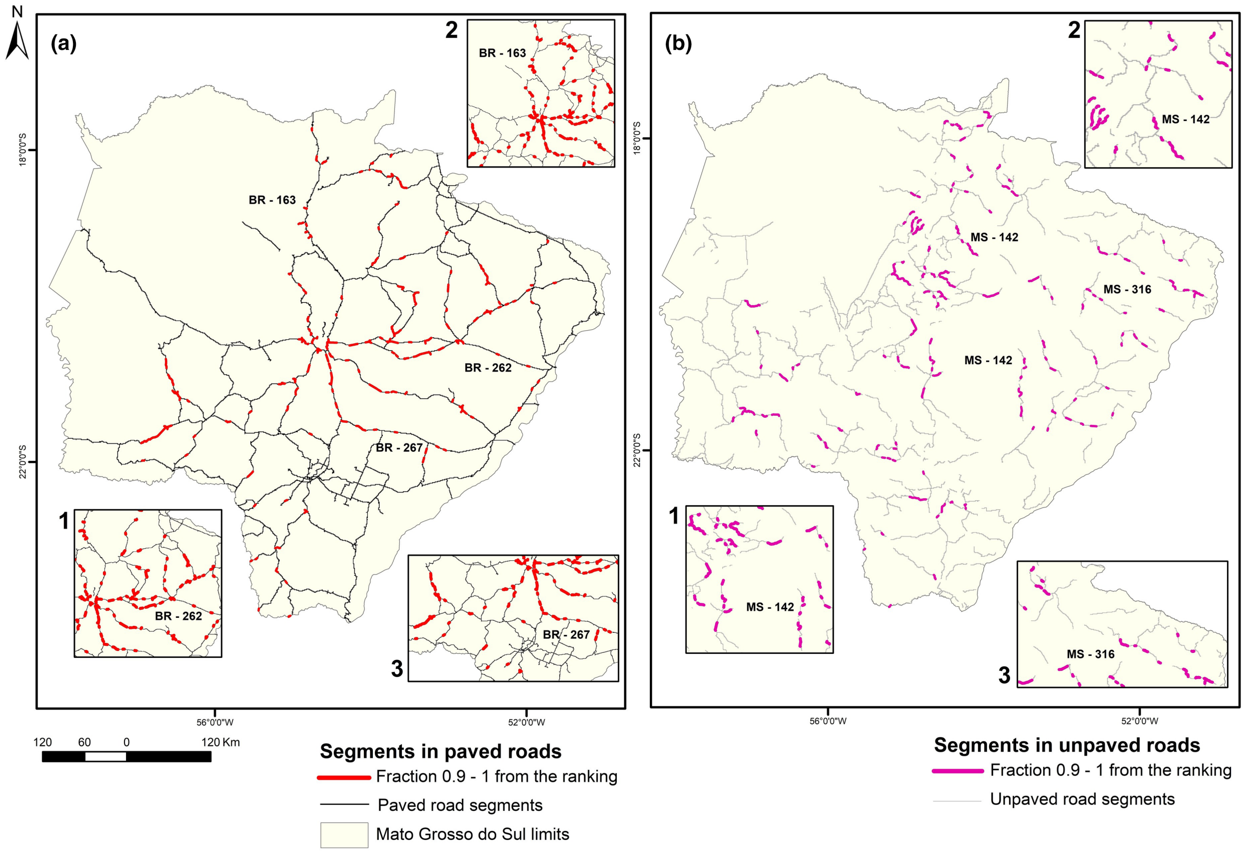

FIGURE 4 Spatial priority segments considering the top >0.9 fraction from the spatial prioritization for paved (a) and unpaved (b) roads. Main roads selected in the prioritization are highlighted in the map, considering all priority segments indicated within the road.

return on investment of the cost of mitigation measures overtime, given the savings from avoided collisions (Ascensão et al. 2021b). Moreover, the results were similar when using as prioritization criteria for the conservation category of focal species. This could be important information while dealing with WVC mitigation agenda.

Using the prioritization process, we aimed to provide decision-makers with tools to assist them with road mitigation planning (Lin et al., 2019). This is especially important for areas where no data are available. Our results revealed areas where mitigation should be considered first to significantly lessen WVC impacts. However, prior to mitigation implementation, and given the large extent of roads classified as a priority for mitigation implementation, it may be desirable to collect data on species abundance and characteristics of the road layout and surrounding areas. The State of Mato Grosso do Sul is in the process of paving many of the unpaved roads and results from our models can help to guide the licensing process of road paving (Saito & Balestieri, 2021).

Fencing combined with faunal passages has been acknowledged as one of the most effective measures to reduce WVC (Seiler et al., 2016; Rytwinski et al., 2016; Spanowicz et al., 2020). There is evidence that several medium and large mammals that inhabit the Mato Grosso do Sul use existing passages (drainage culverts, cattle boxes, and bridges), including tapir, giant anteater and capybara (Abra et al., 2019). However, as there is no associated fencing, the use of these existing passages only occurs opportunistically (Noonan et al., 2021). We highlight that maintaining landscape functional connectivity is essential for wildlife persistence (Ascensao et al., 2019). Hence, channelling these species into existing passages through fences would likely result in higher use of the passages and interchange of individuals between roadside populations.

Our framework can help decision-makers to improve road management and planning. Yet, a key step in this process is the involvement of stakeholders such as government staff (road managers and environment institutions), NGO representatives, consultants and others. Road mitigation planning process will be more successful if there is adequate and effective communication between scientists and decision-makers (Tulloch et al., 2016; Ferraz et al., 2021). In our case, the wide distribution of our focal species results in a large proportion of the road network prone to collision that eventually may cause serious human injuries and material damage. As so, and because the budget is often limited, the decision on where to implement mitigation measures is influenced not only by the modelling outputs but also by political, social and economic criteria, that is where it is less expensive and more feasible to implement mitigation measures (selecting from the pool of priority road sections).

We acknowledge that several improvements within the framework process could benefit the prioritization process. For example, the integration of WVC information from systematic surveys carried out on unpaved roads as well the inclusion of information on traffic volume, road speed and road structural features, such as road profile, the presence of existing crossing structures (Visintin et al. 2016a,2016b; Wright et al. 2020). However, this information is scarce or non-existent for the roads considered. Nevertheless, the outputs of our study are being considered and discussed among different stakeholders, namely road managers, political decision-makers and other entities, for selecting where to instal mitigation measures, namely proper fencing connected to existing passages, in close collaboration with the state road infrastructure agency (AGESUL).

Our study shows that the mitigation of road segments can greatly benefit from the prioritization proposed by our framework, making it a valuable resource for decision-makers. Furthermore, our models highlight that WVC data could be collected only in high-risk areas, contributing to model validation and to avoid monitoring unnecessary areas. Public policy discussions will also gain with our framework use. Investing in modelling tools to assist decision-making can therefore provide a win–win solution for improving traffic safety for humans and reduce road-related negative effects on biodiversity.

AUTHOR CONTRIBUTIONS

Yuri Geraldo Gomes Ribeiro: Conceptualization (lead); data curation (lead); formal analysis (lead); methodology (lead); writing – original draft (lead); writing – review and editing (lead). **Fernando Ascensão:** Conceptualization (lead); supervision (equal); writing – original draft (equal); writing – review and editing (equal). **Débora Regina Yogui:** Data curation (equal); investigation (equal); writing – review and editing (equal). **Katia Ferraz:** Conceptualization (lead); formal analysis (equal); methodology (lead); writing – review and editing (equal). **Arnaud Léonard Jean Desbiez:** Conceptualization (equal); funding acquisition (lead); project administration (lead); resources (lead); supervision (lead); writing – review and editing (lead).

ACKNOWLEDGEMENTS

We would like to thank the donors of the Anteaters & Highways Project especially the Foundation Segre as well as North American and European Zoos listed at (http://www.giantanteater.org/). We also would like to thank all the researchers that collaborated in discussions and ideas for this paper, especially Patricia Medici, Alex Bovo, Andreas Kindel, Bruno Ribeiro, Carolina Ortiz, Rafael Loyola, Vinicius Alberici, Rafael de Morais and many others. YGGR was funded by the Fondation Segré. FA was funded by Fundação para a Ciência e Tecnologia (contract CEECIND/03265/2017). KMPMBF was funded by a research grant (308632/2018-4) from the Conselho Nacional de Pesquisa e Desenvolvimento Científico e Tecnológico (CNPq). DRY was funded by the Nashville Zoo and ALJD by the Royal Zoological Society of Scotland. We would like to thank two anonymous reviewers and editor Nigel Collar for helping to improve this manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article:
Ribeiro, Y.G.G., Ascensão, F., Yogui, D.R., de Barros Ferraz, K.M.P.M. & Desbiez, A.L.J. (2023) Prioritizing road mitigation using ecologically based land-use planning. *Austral Ecology*, 00, 1–13. Available from: https://doi.org/10.1111/aec.13295