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A framework for large-scale risk assessment of road-related impacts, with application to mustelids

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ABSTRACT

Roads, while crucial for human development and economic growth, pose significant threats to biodiversity. Large-scale road risk assessments are essential for guiding infrastructure planning, particularly in identifying areas to avoid new construction or prioritizing regions for mitigation where road networks are already established. However, conducting comprehensive assessments is challenging in regions with limited data on species' responses to roads. In this study, we propose a methodological approach for global and regional risk assessments of road-related impacts, utilizing data on road exposure and species-level susceptibility to road effects. We first derive species-specific susceptibility to road impacts using available trait data and expert knowledge. This information is spatialized through species range maps, creating a cross-taxa susceptibility layer. We then combine this layer with infrastructure density data to produce a bivariate map that highlights the co-occurrence of susceptibility and exposure. Through this approach, we identify priority mitigation areas—regions with high susceptibility and high exposure where mitigation efforts should be concentrated—and priority preservation areas—regions with high susceptibility but low exposure that should be protected from further road development. Our case-study focuses on mustelids, a globally distributed group with significant vulnerability to road impacts yet underrepresented in road ecology studies. The results reveal that the highest-risk areas are concentrated in Eastern Europe, Southeast Asia, and scattered across sub-Saharan Africa, where high conservation value intersects with extensive road networks, marking these as priority mitigation areas. Priority preservation areas span mainly across South America, North America, and Siberia, with some areas across Africa and Borneo. This framework offers a foundation for preliminary assessments and proactive zoning, aiding in the identification of conservation management areas across different infrastructure types and taxa. Its adaptability makes it a valuable tool for researchers, wildlife managers, and transportation planners conducting large-scale assessments of infrastructure impacts on biodiversity.

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1. Introduction

Roads and other infrastructure networks are rapidly expanding around the world, spreading over most of its surface (Laurance et al., 2014; Meijer et al., 2018). When carefully planned and implemented, roads are important assets for improving human life and economic conditions (Cook et al., 2005; Ali et al., 2015). Yet, these infrastructure can also be responsible for significant and deleterious effects on biodiversity, including direct mortality by roadkill, a barrier to animal movement and gene flow, or pollution (Van der Ree et al., 2015; Barrientos et al., 2021). The infrastructure corridors can further improve or provide accessibility of humans to hitherto isolated areas, increasing illegal and exploitative activities such as poaching and the spread of diseases (Laurance et al., 2015; Alamgir et al., 2017). Moreover, roads can be an important driver of the current biodiversity crisis (Maxwell et al., 2016; Driscoll et al., 2018). The IUCN red list has 2703 extant animal species (invertebrate and vertebrate) threatened by road and railway infrastructure, including 276 Critically Endangered, 525 Endangered, 524 Vulnerable, 420 Near Threatened, 104 Data Deficient, and 852 Least Concern (www.iucnredlist.org; assessed 05/11/2024). Yet, this number is likely to be much higher as most human-related threats are associated with road networks. For example, agriculture expansion is intrinsically related to transportation infrastructure (Hess et al., 2013; Ali et al., 2015; Maxwell et al., 2016), and deforestation in tropical forests mainly occurs near roads (Laurance et al., 2009; Barber et al., 2014).

The rapid expansion of infrastructure and the vast number of species at risk underscore the need for comprehensive, large-scale assessments across diverse taxa. This is essential for implementing planning and management programs tailored to each region and its local biodiversity. While some previous studies have developed global zoning plans that balance the environmental costs and social benefits of infrastructure development (Laurance et al., 2014), they often do not focus on specific taxa. Other studies incorporated species-specific approaches that, nonetheless, require detailed knowledge on species traits that are often unavailable (González-Suárez et al., 2018; D’Amico et al., 2019; Biasotto et al., 2021). Here, we suggest a conceptual and methodological framework for the development of global assessments of the risk of impacts related to roads or other linear infrastructure, integrating information from expert knowledge on the exposure of focal species to infrastructure and on susceptibility of focal species to the impacts of the infrastructure.

1.1. Framework description

We posit that the risk of an individual species being affected by roads or other linear infrastructure stems from the interplay between the species’ exposure to such infrastructure and their susceptibility to its impacts (e.g. Visintin et al., 2016; D’Amico et al., 2019;

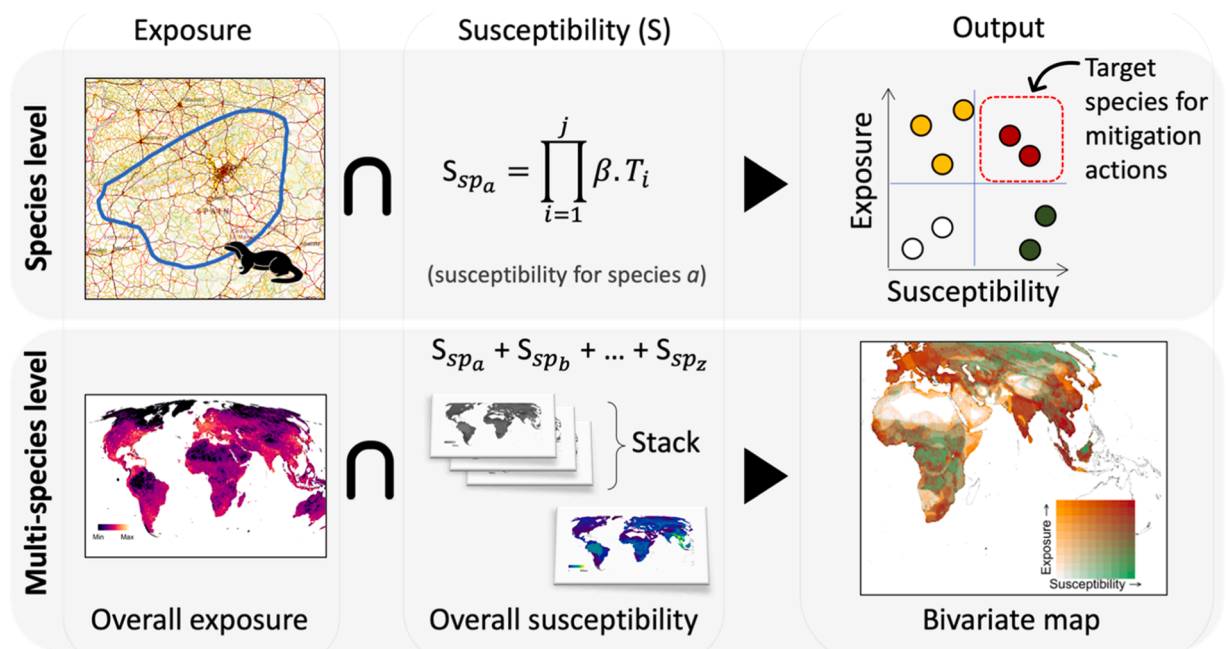


Fig. 1. Conceptual framework outlining the assessment of risks related to linear infrastructure such as roads. The framework integrates exposure (measured by infrastructure density in specific areas, in our case species’ ranges) and susceptibility (likelihood of species being affected by the presence of infrastructure, here determined with the help of expert knowledge) to evaluate potential impacts. Trait-based information (T), like body mass and population trend, can be used to weight (β) species susceptibility. The combined exposure and susceptibility data allow for comparisons across species, aiding in identifying high-risk species for targeted mitigation strategies. The multi-species approach combines overall exposure and overall susceptibility values, generating a comprehensive bivariate map highlighting areas of convergence between infrastructure exposure and species susceptibility.

Biasotto et al., 2021) (Fig. 1). Exposure refers to the infrastructure density (e.g., road density) within the specified area of interest, such as a species range area. It is important to note that exposure can be assessed across varying spatial scales, tailored to the study's objectives, encompassing regional or broader extents, while considering the species' space utilization or distribution patterns.

Susceptibility refers to the likelihood of a species being affected when infrastructure is present, involving direct impacts like mortality or indirect consequences such as increased human access leading to land conversion or poaching. Yet, data on species susceptibility to infrastructure impacts is often limited. One approach to acquire this information involves harnessing trait-based data (González-Suárez et al., 2018). For example, larger carnivores are usually more susceptible to roadkill due to their extensive home ranges and lengthy movement patterns. These attributes increase the likelihood of these species encountering roads, and consequently the risk of collisions (Rytwinski and Fahrig, 2012; Ceia-Hasse et al., 2017). The susceptibility of a species would then be derived by a function weighting the different traits considered (Fig. 1). The selection of traits and their relative weights can be obtained from literature and/or from expert knowledge (e.g., Ascensão et al., 2022). The combined data on species exposure and susceptibility enables comparisons across species, helping to identify those with lower or higher levels of exposure and susceptibility. In particular, this comparison allows highlighting species that have a higher susceptibility and exposure, therefore candidates to be target species for mitigation management actions (Fig. 1).

In a subsequent step (multi-species level), we utilize the exposure across the entire area of interest, alongside the aggregated values of species susceptibility. To achieve this, we spatialize the susceptibility values of each species by assigning these values to their respective spatial distribution or occurrence polygons. Stacking all species layers generates the overall susceptibility layer, summarizing the susceptibility values for the targeted taxa across the study area. This approach differs from simply stacking species richness, as it assigns different weights to species based on their potential susceptibility. Subsequently, overlaying the overall susceptibility layer with the overall exposure layer produces a bivariate map (Fig. 1).

1.2. Application case-study

We applied this framework to obtain a global and regional road related-risk assessments for mustelids. We focused on mustelids as this is a highly diverse group, but also highly vulnerable to road impacts due to their relatively large home-ranges, high mortality rates and delayed maturity (Fahrig and Rytwinski, 2009; Rytwinski and Fahrig, 2012). However, mustelids have not been the focus in road-ecology studies, relative to top carnivores (Schwartz et al., 2020; Barrientos et al., 2021). For example, the IUCN lists 14 mustelid species as being threatened by roads and railways (as of 05/11/2024/). Some of these species are known to be highly impacted by roadkill such as the Eurasian otter (*Lutra lutra*) or the western polecat (*Mustela putorius*), as they live in road-dominated environments, like those from populated Western Europe (Philcox et al., 1999; Jancke and Giere, 2011; Russo et al., 2020). However, other species, such as the Congo clawless otter (*Aonyx congicus*), may not be under direct threat from roads as the forest it inhabits is still well preserved (Gabon and parts of Congo), but the current road openings for wood exploitation is expected to increase poaching and other human-related threats, including overfishing and pollution (Jacques et al., 2009; Brzeski et al., 2016; Wright et al., 2022). Moreover, the mustelid group has a quasi-global distribution and is an ecologically relatively well-known group (Wright et al., 2022), providing quality information for demonstrating our framework's applicability.

Using this framework, we aimed to answer four major questions: 1) Which species may have higher exposure to road impacts? 2) Which species have higher susceptibility to roads? 3) Which species are potentially at higher risk of being impacted by current road networks and which ones are still inhabiting areas of low road exposure? 4) Which regions of the world entail a higher road-related risk for mustelids, and which are still devoid of significant road encroachment for this group?

2. Methods

2.1. Exposure information

Given the global scope of our study, we suggest using the road density within species' range areas as a measure of exposure. To obtain the species-specific exposure values, we calculated the average of road density within each species range. Road spatial distribution was obtained from the Global Roads Inventory Project (GRIP) dataset (Meijer et al., 2018), using the "Total density, all types combined" raster layer, which combines information on highways, primary, secondary, tertiary, and local roads, at a 5 arcminutes resolution for all world countries (ca. 8×8 km).

2.2. Species-specific susceptibility

Following the conceptual framework depicted in Fig. 1, we assumed the following equation to calculate the susceptibility (S) for each species (i):

$$S_i = \log(\text{Body mass}) * \beta * \text{Population trend} \quad (1)$$

where body mass is log-transformed (to remove the effect of few very large species), and β is the median of the scores for the respective level of population trend assigned by experts. These two traits were selected because they are well-documented for the majority of species and are likely to reflect their susceptibility to road effects and vulnerability to such impacts.

Body mass of mammals is known to be correlated with several other traits that shape species' vulnerability to road perturbation and

added mortality, including age at first birth, gestation length, home range and population density (Rytwinski and Fahrig, 2012; González-Suárez et al., 2018). More specifically, larger species tend to have: *i*) longer reproduction cycles (delayed first birth and longer gestation), which may limit the population's ability to balance high unnatural mortality (roadkill and poaching); *ii*) larger home ranges, which increases the likelihood of individuals having roads within their territory; and *iii*) lower population density, thus being more vulnerable to the joint effects of population depletion and stochastic effects (see [Supplementary material S1](#)). As for population trend, we assumed that for species with high susceptibility in areas of extensive road exposure, impacts such as road mortality can pose a serious threat, contributing to population declines.

We used expert knowledge to build this susceptibility parameter, in collaboration with researchers participating in the 33rd European Colloquium of Mustelids (ECM2019), so the data collected pertains to that period. We restricted our analyses to the mustelid species pool for which IUCN provided extinction risk assessments at that time, encompassing 63 species. We collected information from researchers and conservationists working with mustelids through an online questionnaire (see [Supplementary material S2](#)), sent between September and December 2019, distributed by the mailing list of the ECM2019. The mailing list was expanded to include researchers and practitioners known for their work with mustelids across Africa, Asia, North America, South America, and Europe.

Regarding body mass, we first asked researchers if they agreed that the species susceptibility to road impacts should be related to their body mass. The answer to this question could be “yes”, in which case the calculation of the susceptibility would include the (log-transformed) body mass, or “no”, in which case it would be given the value 1 to this criterion. Concerning population trends, we asked researchers to evaluate the relative importance of species with population trends classified as ‘stable’ and ‘decreasing’ compared to those classified as ‘increasing’. The ‘increasing’ category was assigned a default score of 1. Scores for the other categories could range between 1 and 9. For example, if an expert gave a score of 5 to species with ‘decreasing’ population trends, it meant that the responder considered these species to be 5 times more susceptible to road impacts than those species which population trend classified as ‘increasing’. If researchers considered species to be equally important, they could score all species with 1. These questions also aimed to gauge support from researchers and practitioners for our assumption that body mass serves as a key proxy for species' susceptibility to road impacts, while population trend is an important factor to consider when assessing susceptibility to such impacts.

We received 41 valid responses from mustelid experts across the globe. The majority (71 %) agreed that body mass is a reliable indicator of susceptibility to road impacts ([Fig. S2.1](#), [Supplementary material S2](#)). Similarly, only 15 % of respondents assigned equal weight to all population trend levels ([Fig. S2.1](#)). As such, there was a strong support for using these two traits—body mass and population trend—to estimate species' susceptibility to road effects. According to the survey, a decreasing population trend was scored as being six times more relevant compared to an increasing trend. Species with no available population trend data received a median score of 4, while those with stable population trends were assigned a median score of 2.

For obtaining species' range, we used the spatial polygons provided by IUCN, keeping those classified as: *i*) extant, *ii*) native, reintroduced or uncertain origin, and *iii*) resident. We also retained the information from the IUCN assessments regarding the species' population trends (Increasing, Decreasing, Stable and Unknown), and their conservation category: Least Concern (LC), Near Threatened (NT), Vulnerable (VU), Endangered (EN), Critically Endangered (CR), Data Deficient (DD), and Not Evaluated (NE). We collected the body mass of each species from the Body Mass Late Quaternary Mammals database ([Smith et al., 2003](#)).

2.3. Risk assessment

By plotting species-specific susceptibility against exposure, we calculated the relative risk from roads for each species. This allowed us to identify species that exhibited combinations of high or low susceptibility and high or low exposure to roads. For the multi-species assessment, each species' susceptibility value was assigned to its respective spatial distribution polygon(s), which was then rasterized matching the resolution of the road data. By stacking all species layers, we created an overall susceptibility layer, representing the cumulative susceptibility of mustelid taxa globally. We then overlaid this susceptibility layer with the global road density data to produce a bivariate map that illustrates the co-occurrence of susceptibility and exposure. This map allowed us to identify regions with both high susceptibility and high exposure, as well as areas with high susceptibility and low exposure. Thresholds for high and low categories were determined using the 20th and 80th percentiles of the intersected layers. For instance, priority mitigation areas were identified as regions where both susceptibility and exposure exceeded the 80th percentile.

We conducted a more detailed analysis of selected priority areas, applying the same susceptibility and exposure overlay at a regional scale. It is important to note that this was not a simple zoom-in but rather a re-analysis using smaller spatial extents. This step demonstrated the versatility of the framework, showing that it can be effectively applied across different spatial scales.

3. Results

3.1. Species-specific exposure

The three species with the highest exposure, indicated by a higher mean road density within their ranges, were the Japanese weasel (*Mustela itatsi*, NT), Sichuan Weasel (*Mustela russelliana*, DD), and Japanese marten (*Martes melampus*, LC), all having over 1 km/km² of mean road density within their distribution range ([Supplementary material S3](#)). Of the species having a lower exposure to roads, the wolverine (*Gulo gulo*, VU), American marten (*Martes americana*, LC) and Amazon weasel (*Neogale africana*, LC), were those whose distribution range had the lowest mean road density, ca. 0.025 km/km² ([Supplementary material S3](#)).

3.2. Species-specific susceptibility

The species with the highest susceptibility scores were the large marine otter (*Lontra felina*, EN), giant otter (*Pteronura brasiliensis*, EN), and Congo clawless otter (*Aonyx congicus*, NT), all of which exhibit population declines (Supplementary material S3). In contrast, the species with the lowest scores were the Egyptian weasel (*Mustela subpalmata*, LC), sable (*Martes zibellina*, LC), and least weasel (*M. nivalis*, LC). These smaller species have stable or increasing population trends (Supplementary material S2).

3.3. Species-specific risk to road impacts

The arrangement of species-specific susceptibility and exposure data enabled us to visualize the relative risk of species being impacted by roads (Fig. 2). Those species with higher susceptibility and high exposure are candidate to be target species for road mitigation management actions, most notably the smooth-coated otter (*Lutrogale perspicillata*), Asian small-clawed otter (*Aonyx cinereus*), the greater hog badger (*Arctonyx collaris*), or the hairy-nosed otter (*L. sumatrana*), all with decreasing populations. Conversely, those species also having a high susceptibility, but lower exposure should be considered priority focal species for preserving their areas free from roads. This species pool includes the large otters, including the marine otter and giant otter (Fig. 2).

3.4. Multi-species level risk assessment

The sum of the susceptibility of all species provided the overall susceptibility map, with higher values in southeast Asia and South America, including most of the Amazon basin (Fig. 3A). Overlaying the overall susceptibility map with the overall road density information (Fig. 3B) resulted in a bivariate map depicting the infrastructure-related risk for mustelids, which allows distinguishing: i) where higher risk of road related impacts is likely to occur for mustelids, represented by the redder colors, and ii) where higher overall susceptibility overlaps areas of lower road density (greener colors).

Applying the framework at a regional scale allows for a more precise identification of areas where tailored management is needed,

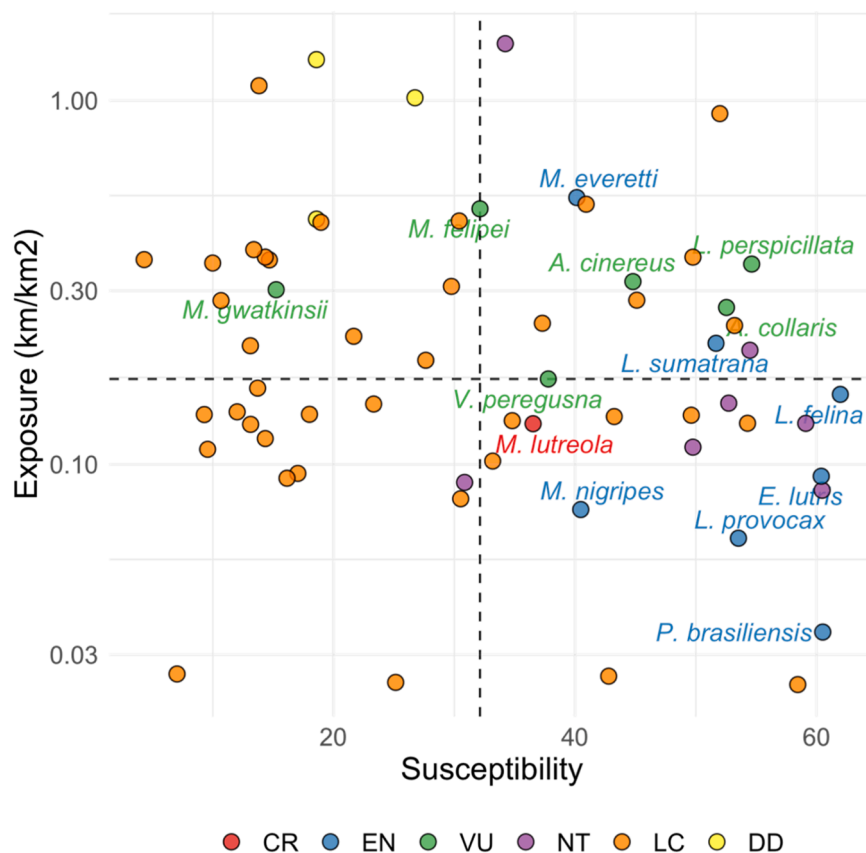


Fig. 2. Scatterplot relating the species-specific susceptibility to road-related impacts and exposure to these infrastructures (measured as the mean road density within range areas). The risk of being impacted by roads increases with increasing susceptibility and exposure, corresponding to the upper-right area of the plot. Species in this quadrant may be considered priority species for targeting road mitigation actions. High susceptible species inhabiting regions with lower road densities are plotted in the bottom-right area and could be considered priority species for preservation actions i.e., maintaining areas free from roads. Species with IUCN conservation category CR, EN, and VU are labelled.

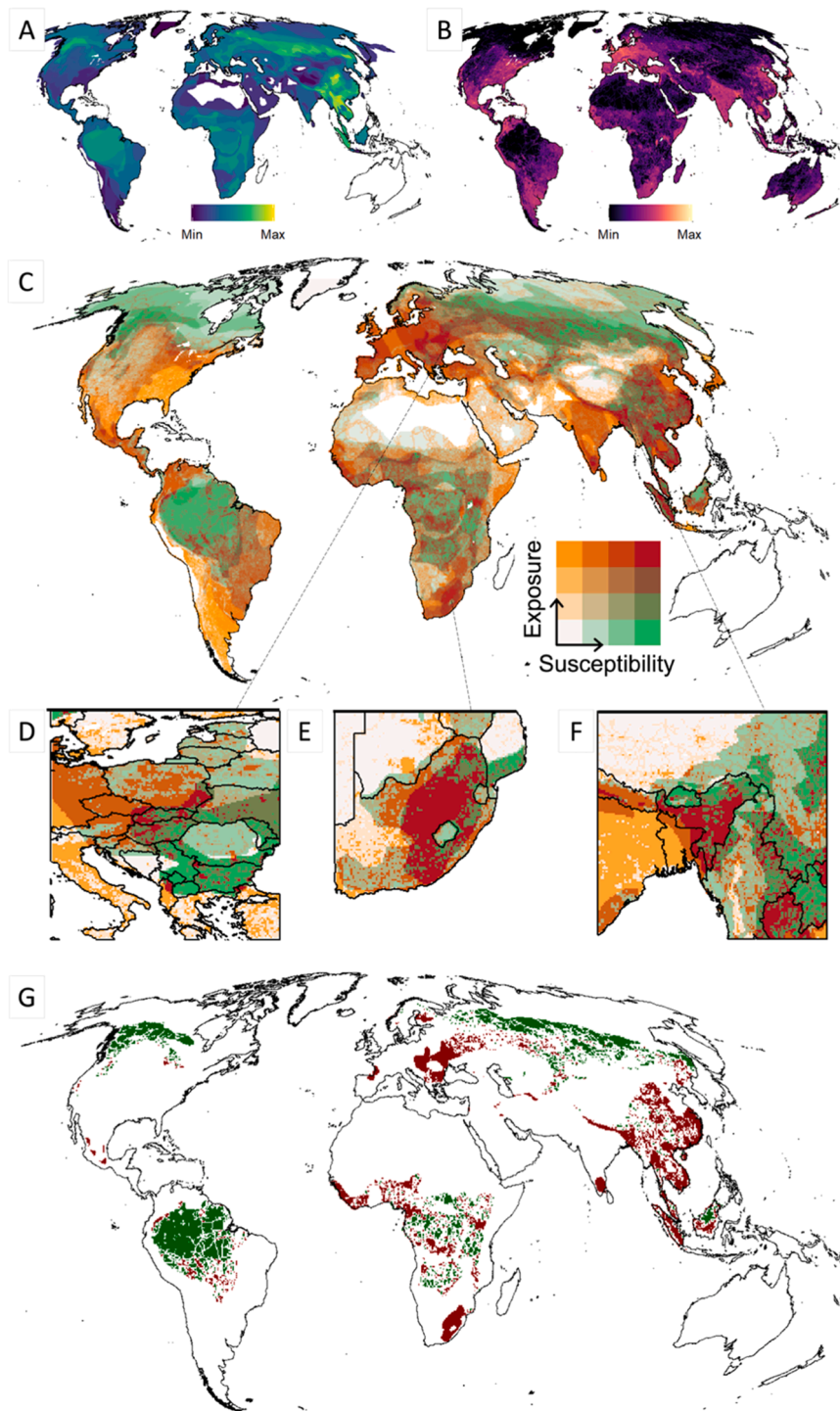


Fig. 3. Spatial distribution of overall susceptibility of mustelids to road impacts (A), overall exposure (B), and risk to road impacts (C). Panels D, E, and F represent the regional assessments in areas of higher risk. Panel G represents priority mitigation areas (red), and the priority preservation areas (green).

such as investing in road mitigation or limiting further infrastructure development. Here, we present regional assessments for Europe, South Africa, and Southeast Asia (Fig. 3D-F). For example, Europe is clearly a continent requiring mitigation measures throughout most its road infrastructure. However, when zooming in, there is a clear contrast between east and Western Europe (Fig. 3D), with investments in mitigation probably being more effective in countries as France, Czechia, or Italy. From the risk map we derived the

priority areas (Fig. 3G), namely the priority mitigation areas in red, and the priority preservation areas in green. Priority mitigation areas span mostly across Eastern Europe, Southeast Asia, and scattered across sub-Saharan Africa and South Africa. Priority preservation areas span mainly across South America, North America, and Siberia, with some areas across Africa and Borneo.

4. Discussion

Our findings indicate that larger species experiencing population declines are particularly vulnerable to road-related impacts, often aligning with species of conservation concern. By identifying species with higher susceptibility to road impacts and those with greater exposure, we were able to pinpoint which species are at the greatest risk due to existing road networks and which are still found in areas with low road exposure. Moreover, our analysis highlighted regions, both globally and regionally, that pose the highest road-related risks, in this case study for mustelids, as well as areas that remain largely free from significant road encroachment.

For highly susceptible species living in regions with significant road exposure, the impacts of roads, particularly road mortality, can be a major threat contributing to their declining population trends. For example, roadkill is one of the major human-induced mortality sources for the European mink (Palazón et al., 2012; Mañas et al., 2016). For other susceptible species, such as the smooth-coated otter, Asian small-clawed otter, or greater hog badger, the impact of roads is less known (Wright et al., 2022). On the other hand, highly susceptible species inhabiting low road-density regions may, understandably, be out of the radar of the IUCN regarding the threat of roads (Wright et al., 2022). In our case study, highly susceptible species such as the large marine otter, giant otter, sea otter, and southern river otter are not listed as being threatened by roads. However, depending on the infrastructure development, namely of deep-water ports and associated road networks in coastal areas, these species may become increasingly threatened by those infrastructure, not only by roadkill during incursions to land (Correa and Pizarro, 2023), but also by other road-related impacts such as chemical pollution (Jessup et al., 2010) or direct disturbance from higher human activity (Carter and Rosas, 1997).

The resultant maps of overall susceptibility, integrating species-specific vulnerabilities to roads, pinpoint Southeast Asia and South America as regions encompassing higher vulnerability to road effects. The overlap between overall susceptibility and exposure identified priority mitigation areas, like Southeast Asia, and priority preservation areas, such as the Amazon basin or Central Asia. According to our assessment, there are few priority preservation areas left across the globe. Aside from the Amazon basin (the largest continuous preservation area), other such areas are found in North America, Siberia, and Borneo, and scattered across Africa. This implies that there are few areas where susceptible species still inhabit roadless or at least low road-density areas, and this is probably true not only for mustelids, but for other species, for example primates (Ascensão et al., 2022). Conversely, priority mitigation areas span across high human density regions, most notably China, together with Southeast Asian countries, and Eastern European regions.

This assessment underscored several regions currently experiencing extensive and unprecedented linear infrastructure development, driven primarily by initiatives such as China's Belt and Road Initiative and the US-led Global Infrastructure and Investment Partnership. Such initiatives will further expose mustelids and all other biodiversity into a higher pressure of direct and indirect infrastructure impacts (Ascensão et al., 2018; Farhadinia et al., 2019; Ng et al., 2020). For example, mega-dams are being built in the world's most biodiverse river basins, not only on the Mekong River basin but also in the Amazon and Congo basins (Winemiller et al., 2016). These dams will require additional roads and the associated powerlines, further fragmenting these regions, increasing habitat loss or degradation. In fact, some 3–5 Mio km of new roads and ca. 2 Mio km of railways are expected to be built worldwide by 2050, together with 16 Mio km of transmission and distribution powerlines by 2030 (Meijer et al., 2018; IEA, 2019, 2020). The bulk of such infrastructure development will occur in developing countries, which may worsen the ability of biodiversity to cope with these infrastructures therein. Our framework can be used as a first assessment, a complementary tool to properly plan and design these infrastructures, to ensure that the potential negative impacts are avoided or mitigated, and the positive aspects are strengthened.

4.1. Limitations to our study

Our framework should be regarded as an initial evaluation procedure on the distribution of the overlap between focal taxa susceptibility to infrastructure impacts and their exposure to such impacts. We note, however, some limitations that should be considered in future developments of this framework. First, the infrastructure mapping in the Global South countries is often incomplete, and therefore priority preservation areas, such as the Amazon basin and other tropical regions, may have more roads than those mapped within the GRIP database (Meijer et al., 2018; Engert et al., 2024). Also, we did not differentiate between various types of roads—such as high-speed highways, regular highways (typically two-lane), and local or rural roads (mostly unpaved)—which can have markedly different impacts on wildlife. Furthermore, some roads may have mitigation measures, such as fencing and wildlife passages, which were not accounted for.

Secondly, we assumed that higher road density has a higher detrimental effect on mustelids, and that all species are (equally) impacted by road density. This may not be the case for more synanthropic species, such as the yellow-throated marten (*Martes flavivula*), that are able to cope with road-related impacts (Dybas, 2017; Lee et al., 2021). However, there is currently little information on species-specific road responsive behavior, precluding the differentiation of the impacts across species. Finally, given the resolution of the IUCN spatial information, our maps are not intended for guiding local conservation actions but to illustrate overall patterns of conservation priorities for mitigating road-related threats to biodiversity, and particularly to mustelids, across the globe (Harfoot et al., 2021). We therefore caution against using these maps to guide local conservation action, whereas they can be a first assessment that should be further investigated through more focused efforts at a smaller scale, depending on target species.

Future developments of this framework could therefore benefit from enhanced infrastructure mapping and detailed road characteristics, enabling the creation of more precise exposure layers. Similarly, insights into the behavior of focal species toward roads and

traffic would refine species-level susceptibility information. Additionally, higher-resolution spatial data on species occurrence would improve the accuracy of priority area delineation.

4.2. Application of the framework

This approach can lay the groundwork for initial assessments and for proactive zoning, identifying priority management areas for both current and future conservation efforts. It is a versatile method, applicable to any infrastructure type and taxa. Studies employing such accessible information to generate preliminary assessments of infrastructure impact on a large scale, ranging from regional to global, can serve as invaluable tools for researchers and wildlife managers. This is especially relevant in developing countries, where information on habitat ecology is often lacking for many species, but which will be highly affected by future infrastructure development (Meijer et al., 2018). Its adaptability makes it a valuable tool for researchers and wildlife managers conducting large-scale assessments of infrastructure impacts on biodiversity. A clear benefit of implementing this framework is the possibility to produce assessments for infrastructure impact in less studied areas, especially relevant in developing countries, which biodiversity will be potentially highly affected by future infrastructure development (Hughes et al., 2020).

Our application to mustelids serves as a demonstration of the conceptual and methodological framework we propose for assessing the impacts of infrastructure on biodiversity. This same approach can be applied to virtually any other taxa, only needing information on species susceptibility, potentially derived from expert-knowledge or published information, and the spatial distribution infrastructure (D'Amico et al., 2019; Ascensão et al., 2022). It should be noted that, while we used body mass as a proxy for species' susceptibility, other traits may be more suitable for different taxa. For instance, traits such as the number of reproductive events per year may be more relevant for amphibians, as they better reflect the capacity of amphibian populations to reproduce and withstand increased road mortality and other adverse impacts (Pincheira-Donoso et al., 2021).

The two types of priority areas highlighted require different management approaches, and our method adds value by mapping them effectively. For priority mitigation areas, a primary management action should be halting habitat loss and environmental degradation processes to reconnect habitat fragments. For example, several studies have shown that wildlife road-crossing structures are effective in reducing roadkill and improving mustelid movement across roads (Clevenger et al., 2001; Ascensão and Mira, 2007). Such road passages should be equipped with properly designed anti-climbing fences, to route animal movement towards the entry of the crossing structure. Both wildlife road-crossing structures and road fences are expensive infrastructures, and their implementation should be prioritized in correspondence with the most likely movement corridors for the target species (Ascensão et al., 2019).

In contrast, for priority preservation areas the primary goal is to avoid adding roads to those well-preserved regions as it will inevitably increase human activities, which in most cases are detrimental to biodiversity and their habitat (Laurance and Arrea, 2017). Likewise, the creation and maintenance of ecological corridors across high-quality habitat areas must be an essential component of all conservation planning. Maintaining the existing priority preservation areas and creating ecological corridors that link them are imperative in areas where massive infrastructure development is expected.

In conclusion, our framework provides a foundational approach for assessing road impacts across taxa and geographic regions. Given the accelerating pace of global infrastructure development, particularly in biodiversity-rich regions, our approach can inform more strategic, large-scale planning to mitigate biodiversity loss, balancing the demands of development with the imperative to protect vulnerable species and habitats.

Ethics Statement

Not applicable: This manuscript does not include human or animal research.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.gecco.2024.e03329](https://doi.org/10.1016/j.gecco.2024.e03329).

Data availability

No data was used for the research described in the article.

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