Conservation threats from roadkill in the global road network

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CONSERVATION THREATS FROM ROADKILL IN THE GLOBAL ROAD NETWORK

Short running title: CONSERVATION THREATS FROM ROADKILL

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BIOSKETCH

Clara Grilo is particularly interested in applied ecological questions to provide scientific underpinnings for the preservation, management, or restoration of wildlife and landscapes. Over the last years, much of her research focused on the effects of road network on birds and mammals such as behaviour, relative abundance, genetic structure, risk of mortality and population viability. The research interests of this team include road ecology, macroecology, macroevolution, extinction risk and global change biology. The shared interests in these fields were combined to advance our understanding of the impact of roadkill on wildlife populations.

AUTHOR CONTRIBUTIONS

C.G. and P.B. conceived the idea. C.G., K.S., A.R., E.K., F.Z.F, S.A.G. and Y. W. collected the data. C.G, L.B.A. and E.G. designed the methods. C.G and E.G. analyzed the data. M.G.S. prepared the final map. C:G. led the writing of the manuscript and all authors contributed critically to the drafts and gave final approval for publication.

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ABSTRACT

Aim – The road network is increasing globally but the consequences of roadkill on the viability of wildlife populations are largely unknown. We provide a framework that allows us to estimate how risk of extinction of local populations increases due to roadkill and to generate a global assessment that identifies which mammalian species are most vulnerable to roadkill and the areas where they occur.

Location - Global

Time period – 1995 -2015

Major taxa studied – Terrestrial mammals

Methods – We introduce a framework to quantify the effect of roadkill on terrestrial mammals worldwide that includes three steps: 1) compilation of roadkill rates to estimate the fraction of a local population killed on the roads, 2) prediction of population risk of extinction based on observed roadkill rates (for a target group of species of conservation concern and non-threatened species with high roadkill rates), and 3) global assessment of vulnerability to roadkill for 4,677 terrestrial mammalian species estimated using phylogenetic regression models that link extinction risk to demographic parameters.

Results – We identified four populations among the 70 species in the target group which could become extinct in 50 years if observed roadkill levels persist in the study areas: maned wolf *Chrysocyon brachyurus* (Brazil), little spotted cat *Leopardus tigrinus* (Brazil), brown hyena *Hyaena brunnea* (Southern Africa) and leopard *Panthera pardus (*North India). The global assessment revealed roadkill as an added risk for 2.7% (n=124) terrestrial mammals, including 83 species Threatened or Near Threatened. We identified regions of concern that concentrate species vulnerable to roadkill and high road densities in areas of South Africa, central and Southeast Asia, and the Andes.

Main conclusions – Our framework revealed populations of threatened species that require special attention and can be incorporated into management and planning strategies informing road managers and conservation agencies.

Keywords: Mammals; roadkill; life-history; risk of extinction; road mitigation; road network;

Main text

1. INTRODUCTION

There are at least 36 million kilometres of roads in the world currently (CIA, 2020). Roads dominate the landscape in some regions, e.g., 83% of land in the USA (Riitters & Wickham, 2003) and 50% in Europe (Torres et al., 2016) are within 1 and 1.5 km of the nearest road, respectively. An additional 25 million kilometres of roads are expected by 2050, mostly from expanding the road networks of developing countries that contain exceptional biological diversity and highly conserved ecosystems (Laurance, 2018; Meijer et al., 2018; Alamjir et al., 2019). Given the potential for roads to negatively affect biodiversity, evaluating the current and future impacts of the global road network on wildlife is critical (van der Ree et al., 2015). Wildlife mortality through collisions with vehicles (hereafter roadkill) is often considered one of the most serious impacts of roads, being a significant source of anthropogenic mortality for some species (Loss et al., 2015; Hill et al., 2019; Morelli et al., 2020). Roadkill impacts have been well documented for a wide range of vertebrates and regions, with estimates of millions of individuals dying annually in roads across Europe (e.g. Erritzoe et al., 2003; Wembridge et al,. 2016; Grilo et al., 2020), the Americas (e.g. Loss et al., 2014; Baxter-Gilbert et al., 2015; González-Suaréz et al., 2018) and Australia (Ehmann & Cogger, 1985), and roadkill being identified as a problem also in Africa (Collinson et al., 2019; Gandiwa et al., 2020) and Asia (Seo et al., 2015; Silva et al., 2020). While numbers killed are high, the actual impact of that added mortality at the population level is poorly understood, but at least for some species it can be high (Benítez-López et al., 2010). For instance, roadkill is responsible for 35% of annual deaths in Florida panthers *Puma concolor coryi* (Taylor et al., 2002) and 49% in badgers *Meles meles* in Britain (Harris et al., 1992, Harris et al., 1995). Also, roadkill annually removes 10% of the Iberian lynx *Lynx pardinus* population (Simón et al., 2012), 10% of black bears *Ursus americanus* in Ocala National Forest (FFWCC, 2012) and may have reduced the density of hedgehogs *Erinaceus europaeus* in the Netherlands by 30% (Huijser & Bergers, 2000). Overall, it is likely that roadkill can increase the risk of local extinction by reducing effective population size and genetic diversity, and by limiting demographic and genetic rescue (Jackson & Fahrig, 2011). There is, therefore, a critical need to identify the species and regions that are most vulnerable to the rapid expansion of roads and traffic worldwide (Laurance et al., 2014). A challenge to achieve this goal is that wildlife populations do not respond equally to additional mortality, which makes evaluation of roadkill effects on population persistence challenging (Gibbs & Shriver, 2005; Row et al., 2007; Diniz & Brito, 2013, Ceia-Hasse et al., 2017). These effects may vary depending not only on the proportion of the population killed on roads each year (Jaeger et al., 2005; Jacobson et al., 2016) but also on demographic processes (e.g., density dependent fecundity or immigration) that affect the ability of the population to offset increased mortality (Purvis et al., 2000; Pearson et al., 2014). Species characteristics can help us predict these variable effects. For example, species with high adult survival and low fecundity, typically have low population growth rates, and are more likely to experience declines with added anthropogenic mortality (Sparkman et al., 2011). The link between species demographic variables and risk of extinction due to additional mortality has been established for some sources of human impacts (Owens & Bennet, 2000; Crooks et al., 2017) but not for roadkill (but see Grilo et al., 2020 that estimated the incidence of roadkill based on species trait-models and estimated population vulnerability in Europe).

In this study, we present a framework that allows us to generate the first global assessment of vulnerability to roadkill in mammals (Figure 1). Within this framework we first analysed a unique global dataset of observed roadkill rates using spatially implicit population models to estimate the increase in risk of extinction due to roadkill in multiple local populations. We then use trait data and phylogenetic predictive regressions to identify mammalian species most vulnerable to roadkill and the areas where they occur. Our findings offer insights into the risks that roads pose to wildlife currently and identifies areas where roadkill can lead to loss of mammalian biodiversity. This information can provide initial guidance to prioritize conservation and mitigation efforts to meet sustainable development goals in countries with high biodiversity. More generally, the proposed framework could be integrated into existing risk assessment protocols and expanded to other taxonomic groups.

2. MATERIAL AND METHODS

Our framework includes three steps which we explain in detail below. In summary, the first step generated estimates of the fraction of a local population killed in vehicle-wildlife collisions; the second step predicted the risk of extinction from that added mortality for target populations; and the third step used identified relationships in the target group to predict vulnerability to roadkill for 4,677 terrestrial mammals.

Step 1: Roadkill rates and estimated fraction of the population roadkilled per year

To estimate roadkill rates, we conducted a systematic literature search and located unpublished data to compile roadkill counts for mammals collected between 1995 and 2015 in any areas of the world (Figure 1). Peer-reviewed and grey literature were located searching the Web of Knowledge, Science Direct and Google Scholar using combinations of the following search terms: “mammal*” and all related taxonomic orders combined with “roadkill* or “road-kill” or “road mortality” in five languages (Chinese, English, Portuguese, Russian and Spanish). We only compiled roadkill counts from surveys completed before the end of 2015 that surveyed more than 3 km of road for a minimum period of one month (SM1). For each species and study we used these counts (reported number of roadkilled individuals) to calculate annual roadkill rates (roadkilled individuals per km of road surveyed per survey effort in days) using two different approaches to account for the lower detectability and persistence in roads of small sized carcasses (small carcasses do not persist in the road as long as larger ones, Santos et al., 2016). For species with average body size <1 kg, we calculated annual roadkill rates as: (count/km of road sampled /number of surveys)*365 days, where the number of surveys is the total number of days in which surveys were completed. For species with average body size > 1kg we calculated annual roadkill rates as: (count/km of road sampled /total survey period)*365 days, where total survey period is the number of days between the first and the last survey day. This assumes that larger mammals killed during the survey period would always be detected, but that some small species could be missed as they could disappear between survey intervals. The two methods are equivalent for daily surveys.

For a target group of species for which roadkill rates were available we then estimated the fraction of the population roadkilled in the study areas, selecting estimates from the site with the highest observed roadkill rate if multiple estimates were available. The target group included all mammalian species of conservation concern (i.e., Near Threatened, Vulnerable, Endangered, or Critically Endangered species classified by IUCN Red List 2016) and those species with high roadkill rates: the three small-sized (<1kg) and the three large-sized (>1kg) mammals with the highest roadkill rates in each continent [North America (Canada, USA and Mexico), Central/South America, Europe, Africa, Asia and Oceania]. For each species, we assumed observed roadkill rates were representative of all paved roads (excluding urban areas) in the *study site*, which was defined by using a buffer around the centroid of the actual surveyed road. The buffer was defined to potential encompass a local population considering species area requirements vary with body size (Jetz et al. 2004). We considered a 5km radius buffer for species with body mass <1kg, and a 50km radius for mass >1kg.

The fraction of a population lost to roadkill was calculated as $F_{Roadkill} = N_{roadkilled}/N_{pop}$, where $N_{roadkilled}$ is the estimated total number of roadkilled individuals of the species in the *study site* (ind/km), calculated by multiplying the observed roadkill rate by the total length of paved roads in the study site. Road length was estimated using Google Earth (Digital Globe 2016. http://www.earth.google.com [2015-2016]. N_{pop} is an estimate of the total population of the species in the *study site* calculated by multiplying observed population density (ind/km^2) by study site area (km^2). Population density estimates were obtained from within or near the *study site* when possible; otherwise we used published species-level estimates (see SM2 for references). Although we had a single observed roadkill rate for each species in each study site, we often found multiple estimates of population density from different sources. We used the minimum and maximum estimates of population densities to calculate several $F_{Roadkil}$ values and reflect uncertainty.

Step 2 Risk of extinction from roadkill for the target species

We used a spatially implicit age-structured stochastic population model based on Borda-de-Água et al. (2014) to estimate the increased probability of extinction in 50 years (based on 600 simulations) for each selected species in its study site under simulated scenarios of $F_{Roadkill}$ values ranging from 0.01 to 0.9 at 0.01 increments (methodological details and code in SM3; Figure 1). Without roadkill all species had stable populations with no risk of extinction within 50 years. These simulations allowed us to estimate the increased probability of extinction given the observed $F_{Roadkill}$ for each selected species. For species with multiple $F_{Roadkill}$ we reported the range based on the minimum and maximum fractions. In addition, we defined a threshold value, $F_{RiskExt10,}$ to represent the proportion of the population that if roadkilled would result in an increase in the probability of extinction of 0.1. $F_{RiskExt10}$ could be higher or lower than the observed $F_{Roadkill}$. We propose $F_{RiskExt10}$ as an indicator of vulnerability to roadkill, with species in which loss of small fractions of a population can result in increased risk of extinction (small $F_{RiskExt10}$) being more vulnerable and more likely to be threatened by roadkill.

The Borda-de-Água et al. (2014) model assumes that population growth is determined by age at first birth, interval between births, litter size, period of recruitment (the average interval in months between two births by an adult female), number of litters per year, natural survival rates for nine variables: newborns/youngest individuals, juveniles, and adults (categories reflect those in the study from which survival data were obtained, see below), and maximum longevity. Estimates for these variables were obtained from available compilations (Jones et al., 2009; Myhrvold et al., 2015; Myers et al., 2016; WildScreen Arkive, 2016; IUCN, 2016) and dedicated literature searches (SM2). For survival rates we used any available data, and in some cases we applied the single estimate available to all age-stages. When data were not available for a species we used the median from all available estimates from closely related taxa/species or from the most closely related species (same genus). A total of 68 cases out of 710 ((population density + nine variables) * 71 populations) were missing data being the majority on survival rates (details in SM2). We used empirical estimates of variance for all variables when available; otherwise we used a 10% variance.

The Borda-de-Água et al. (2014) model incorporates density dependence using the Beverton-Holt relationship between the number of births and juveniles (Beverton & Holt, 1957). By applying this model we assumed that: roadkill rates were constant over time in each study site, the available data reflected dynamics reasonably well even if obtained from other regions, and the population in the study site was not part of a metapopulation.

Step 3. Global assessment of mammalian vulnerability to roadkill

The population models described above were computationally intensive and to estimate $F_{RiskExt10}$ for all terrestrial mammals (n=4,677) worldwide we used a phylogenetic predictive model fitted for the target group (see SM4 for further details). First, we identified the demographic variables that best explain $F_{RiskExt10}$ for the target group species (step 1 – n=71) fitting both (non-phylogenetic) generalized least squares regression (GLS) and phylogenetic GLS (PGLS) models (see SM4 for further details). We then applied the phylogenetic imputation method using the demographic variables that better explained $F_{RiskExt10}$ to predict the missing values of $F_{RiskExt10}$ for the remaining mammals (see Stearns 1983; Guénard et al. 2011) (SM4). To identify regions of concern, we mapped the overlap between the species most vulnerable to roadkill ($F_{RiskExt10}$ <0.2) and the global road network using a 100-km x 100-km grid cells with a Cylindrical Equal Area projection. Species presence was determined using current native distribution data (IUCN, 2019) selecting polygons classified as presence: Extant, Probably Extant and Possibly Extant; origin: Native, and Reintroduced; and seasonality: Resident, Breeding Season, and Non-breeding Season. To quantify the kilometres of roads in each grid we used data from Meijer et al. (2018) selecting all roads classified as highways and primary roads, and all roads with road surface classified as paved.

Validation

Step 2 generated estimates of risk of extinction from roadkill (anthropogenic mortality) for local populations. Ideally, those estimates could be compared with population trends in those locations for validation, but those data are simply not available. Instead, we conducted a qualitative validation searching the literature for independent evidence from population viability analyses or other modelling approaches showing the effects of anthropogenic mortality on risk of extinction. We considered mortality from roadkill and other human-driven sources, as analyses of roadkill impacts are very limited. The comparison focused on evidence from those species identified as most vulnerable in our assessment ($F_{RiskExt10}$ <0.20, n=9) and those identified as least vulnerable ($F_{RiskExt10}$ >0.90, n=15). For step 3, we validated model estimates of $F_{RiskExt10}$ using leave-one-out cross-validation (LOO-CV) (Bruggeman, 2009) as well as 2-fold and 5-fold cross-validation blocked by phylogenetic distance (Roberts et al., 2017) (see SM4 for further details).

3. RESULTS

3.1 Roadkill rates and population responses to roadkill

We compiled a total of 1,310 roadkill rate records for 392 different mammalian species representing 184 references and personal communications (SM1). We found high inter- and intra-specific variability in roadkill rates (SM1). Roadkill rates varied from fewer than 0.005 ind/km/year (n=16 species) to more than 10 ind/km/year (n=10 species). The large mammal with the highest number of records (moose (*Alces alces*); n=45) had roadkill rates ranging between 0.00015 and 1.17 ind/km/year (SM1), while the small mammal with the highest number of records (guinea pig (*Cavia aperea*); n=9) had roadkill rates ranging between 0.004 and 12.82 ind/km/year.

Average roadkill rates were lower for species of conservation concern (0.09 ind/km/year) than for least concern species (0.44 ind/km/year). We obtained roadkill estimates for 61 species of conservation concern (four species in North America, 14 in Central/South America, eight in Europe, six in Africa, 23 in Asia, and six in Oceania; SM1). Thirty-six species were identified as top-roadkilled in the six continents resulting in a selected subset of 97 species. We obtained population density estimates for 70 of these species (SM2). Since we obtained roadkill records of leopard *Panthera pardus* in Africa and Asia, we analysed 71 populations of 70 species (SM2).

Our population models suggest populations of four species in the target group may be at risk of extinction if observed roadkill levels persist on the study sites including the maned wolf *Chrysocyon brachyurus* in Uberlândia-Uberada (Brazil), little spotted cat *Leopardus tigrinus* in western Santa Catarina (Brazil), brown hyena *Hyaena brunnea* in Mapungubwe Transfrontier conservation area (Southern Africa), and leopard *Panthera pardus* in Rajaji National Park and the Hariwar Conservation area (North India) (Figure 2; details in SM5 and SM6). Among the 71 populations analysed, we classified 10 as most vulnerable to roadkill ($F_{RiskExt10}$ <0.2), 31 had intermediate vulnerability (0.2< $F_{RiskExt10}$<0.5), 15 had low vulnerability (0.5< $F_{RiskExt10}$<0.9), and 15 had very low vulnerability ($F_{RiskExt10}$>0.9) (Figure 2, SM6).

Results from the qualitative validation largely supported our assessment: while 60% of the nine most vulnerable species ($F_{RiskExt10}$ <0.20) had published studies showing non-natural mortality can increase risk of extinction for those species, only 13% of the 15 species with very low risk ($F_{RiskExt10}$ >0.90) had published studies showing non-natural mortality can pose a threat (SM7).

3.2 Terrestrial mammals potentially threatened by roadkill

Phylogenetic predictive model showed that high reproductive rates, represented by low age of maturity, high numbers of litters per year and large litter sizes, were key predictors of high $F_{RiskExt10}$ (details in SM8). The use of the proposed phylogenetic predictive models was supported during validation, with a strong correlation (R^2=0.69) between observed and imputed $F_{RiskExt10}$ risk (SM). Predicted $F_{RiskExt10}$ identified 2.7% of mammals (124 species out of 4,677) as most vulnerable to roadkill ($F_{RiskExt10}$<0.2) including 83 species Threatened or Near Threatened by other human activities, but also 18 Least Concern species (23 species were not evaluated) (see SM9 for complete list of species vulnerability). Surprisingly, IUCN only considered roadkill as a threat to only 10 out of 5940 mammalian species which, according to our estimates are not among those most vulnerable to roadkill ($F_{RiskExt10}$ < 0.20). Particularly vulnerable species ($F_{RiskExt10}$ <0.10) included: wild yak *Bos mutus* (listed as Vulnerable by the IUCN), Bohor reedbuck *Redunca redunca* (Least Concern), Amur tiger *Panthera tigris altaica* (Endangered), African elephant *Loxodonta africana* (Vulnerable), sun bear *Helarctos malayanus* (Vulnerable), African buffalo *Syncerus caffer* (Near Threatened), Asian elephant *Elephas maximus* (Endangered) and Sumatran rhinoceros *Dicerorhinus sumatrensis* (Critically Endangered) (SM8).

Mapping richness of species identified as most vulnerable to roadkill and existing road densities together revealed several areas of concern where high numbers of most vulnerable species coincide with high road densities, including parts of South Africa, Ghana, central and Southeast Asia, the Malay archipelago and the Andean region (Figure 3). Parts of Sub-Saharan Africa, Amazon, Mongolian plateau, and the Palearctic tundra concentrate vulnerable species but currently have low densities of paved roads (“future risk zones”). Europe, North America and many areas of central and South America and coastal Australia represent human-dominated areas with high road density but low numbers of species particularly vulnerable to roadkill. Finally, deserts and the Artic appear as “untouched” areas with no species particularly vulnerable to roadkill and few paved roads.

DISCUSSION

Preventing the impact of roadkill on wildlife requires identifying which species could have increased risk of extinction from the added risk of road mortality. Here, we proposed a framework that produces two key outputs: local evaluations of extinction risk associated with observed roadkill, and a global assessment of vulnerability to roadkill. This framework goes beyond quantifying numbers of roadkill individuals and moves the field of road ecology towards a more comprehensive understanding of the long-term consequences of observed road mortality for multiple species. We show that local high roadkill rates do not necessarily mean that a high fraction of the population will be lost, and that, even with relatively high roadkill rates, populations may be able to persist into the future (Cardillo et al., 2004; Borda-de-Água et al., 2014). However, road projects can pose an additional threat to species of conservation concern that are particularly vulnerable to traffic due to their characteristics and behaviour towards roads (Jacobson et al., 2016; González-Suaréz et al., 2018). Our analyses identified populations of several species of conservation concern (IUCN, 2018) that could become extinct if observed roadkill rates persist in their respective study areas, including the maned wolf and little spotted cat in South America, brown hyena in Africa, and leopard in Asia.

Global assessments such as the one presented here provide the opportunity to identify unstudied or undetected species potentially vulnerable to road mortality impacts and generate a priority map that reveal areas where mammalian biodiversity could be negatively affected by existing and future roads. Applying our framework at a global scale, we identified more than 100 mammals as very vulnerable to roadkill and revealed several areas where mammalian biodiversity may be lost due to the impact of existing road infrastructure. While our results emphasize global findings, the proposed framework can inform conservation prioritization and mitigation efforts both at regional and broad scales as it produces output at local scales already and step 3 could be easily adapted to different spatial and taxonomic scales.

We found that variation among species in their vulnerability to roadkill was in part associated with reproductive traits. Traits associated with faster, more frequent reproduction predicted population resilience to additional mortality, with less impact for species that mature early and have multiple large litters per year (see also Rytwinsky & Fahrig, 2012). Our model predicts these species will have increased risk of extinction only if there is a very high proportion of individual loss (>0.90), a pattern also suggested by previous studies focused on other sources of non-natural mortality (e.g. Garcia et al., 2008, Hurchings et al., 2012; Wang et al., 2018). This is consistent with the hypothesis that faster life histories can protect species from increased mortality risk, suggesting species with slow reproductive rates, and regions were these species are found, should receive more attention when considering roadkill mitigation strategies (e.g. Ceia-Hasse et al., 2017; Pinto et al., 2018). Combining species vulnerabilities with existing road maps, we identified areas where road infrastructure can result in important loss of biodiversity. In particular, Sub-Saharan Africa and south-eastern Asia are areas of concern, where many species vulnerable to roadkill co-occur. These regions also have a high number of threatened mammalian species with declining population (Ceballos et al., 2017) and are already impacted by widespread deforestation (Kleinschroth et al., 2019), commercial poaching (Steinmetz et al., 2006) and mineral exploitation (Laurance et al., 2015). The added impact of mortality due to roads for many mammalian species reveals the need to include the effect of roadkill on cumulative road impact assessments to biodiversity conservation (e.g. Alamgir et al., 2019; Kleinschroth et al., 2019).

Our study presents a new framework for identifying, ranking and predicting species and areas vulnerable to roadkill impacts. This can be a powerful tool to understand risk but there are data and modelling limitations that need to be considered. First, the majority of road surveys only indicated the number of carcasses recorded overall. These estimates can be biased by low carcass detectability and high removal rates (e.g. Santos et al., 2016). Several studies have proposed correction indexes for specific taxa based on the time interval between surveys, the taxonomic group and the species body mass (e.g., Santos et al., 2011; Teixeira et al., 2013). However, it is not clear whether these regional corrections can be extrapolated for mammals worldwide. Second, the modelling approach applies the highest observed roadkill rate for a specific surveyed area (one or several roads) to the entire paved road network in our defined study area, which for large body mass mammals could cover over 7,854 km^2. Currently, there is no scientific consensus regarding how different types of paved roads and associated traffic influence roadkill risk (see Seiler, 2003; Bissonette & Kassar, 2008, Grilo et al, 2015; Sadleir & Linklater, 2016). Further research is needed to determine how varying traffic volume, road widths and types of roadside vegetation influence roadkill rates for a wide range of species. Third, our modelling approach does not consider that roadkill may impact some groups of individuals within a species more than others. Given the same fraction of a population removed by roadkill, population persistence would be different if those removed are primarily reproductive adults *vs*. older animals. For some species there is a high incidence of mortality of juveniles and sub adults while for other species no distinct vulnerability was found among individuals (Grilo et al., 2009). Fourth, for many mammalian species, non-natural mortality includes sources other than road mortality such as legal hunting and poaching (Hill et al., 2019), but our model only considers road mortality. To better understand overall extinction risk for particular populations and species we need to understand all sources of mortality and explore whether non-natural mortality sources may be compensated. Finally, our approach relied on trait data that was largely obtained from global datasets that do not reflect regional and local variation. One example is population density, which was critical to estimate the fraction of the population roadkilled at the regional level. While we cannot overcome this limitation, our approach explicitly included this uncertainty by considering both the minimum and maximum densities observed, which allowed us to estimate a range of fractions of the population roadkilled and, therefore, a broad-spectrum of extinction risks.

Detailed local data are rarely available, but we do acknowledge that population density variation can be important to understand dynamics and extinction risk (González-Suárez & Revilla, 2013; González-Suárez et al., 2015) with the exploration of scenarios for those species we identified as most vulnerable to roadkill impacts. While compiling improved datasets for all species will not be possible, our study offers some guidance for prioritization of data collection: fundamental research for reliable estimation of the size or density of animal populations and survival rates are critical to improve the accuracy of the population model outputs.

CONCLUSIONS

Results of this study have implications for mammalian conservation and road mitigation worldwide. Our analyses bring attention to Sub-Saharan Africa and south-eastern Asia as regions where roads can lead to loss of mammalian biodiversity and thus, areas where future road development and road mitigation need to be carefully considered. The positive news is that these areas (as well as Latin America) have been identified as threat refugia for vertebrates where conservation actions are likely to succeed (Allan et al., 2019).

The local scale output from our framework provides a first step to highlight populations which might be currently under risk of extirpation and areas where local studies are needed to ultimately make site-specific recommendations for road mitigation. This local scale analysis could be directly used in environmental impact studies applied to target areas and species to provide estimates of risk of extinction and potential scenarios given data uncertainty and alternative management plans (Alamgir et al., 2017; Ceballos et al., 2017). "Since IUCN Red List assessments describe ongoing and future threats to each species, our study can directly inform these descriptions by providing information about which species are affected by roadkill and about the severity of that threat. Combining our approach with information on planned infrastructures could additionally identify and quantify the severity of future threats. In addition, the global scale output of our proposed framework could be part of strategic environmental, social and economic assessments by national infrastructure planning agencies, environmental governance agencies, global financing institutions, international NGOs. Projecting risk of extinction across broader areas and taxonomic groups could support decisions towards infrastructure that remains more sustainable throughout its life cycle. Our approach could be directly integrated into existing assessment frameworks, adding a relatively unstudied dimension. For example, the World Bank is the largest source of financing for development and has recently updated its Environmental and Social framework (ESA) to minimize the negative impacts of the projects it finances (Morley et al., 2020). Frameworks such as the ESA could incorporate our approach as an additional module to identify vulnerable areas and species and guide strategies to minimize long-term impacts of proposed road projects. In addition, we generate output for mammals that can be valuable. The global list of mammals vulnerable to roadkill generated here may be used by road managers and conservation agencies in the design of surveys, monitoring, and mitigation measures. The global map identifies regions that deserve special attention and can be particularly relevant for large-scale projects, such as the Belt and Road Initiative, providing information to facilitate addressing all impacts before projects begin (Ascensão et al., 2018).

Predictions and management implications of our framework can be refined once additional roadkill, population density data and demographic become available. The development of tools for global spatial prioritization and strategic road planning, such as the framework presented here for the impact of mortality, are critical to ensure wildlife protection and achieve sustainable transport infrastructure development and should complement other negative road effects on wildlife.

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FIGURES

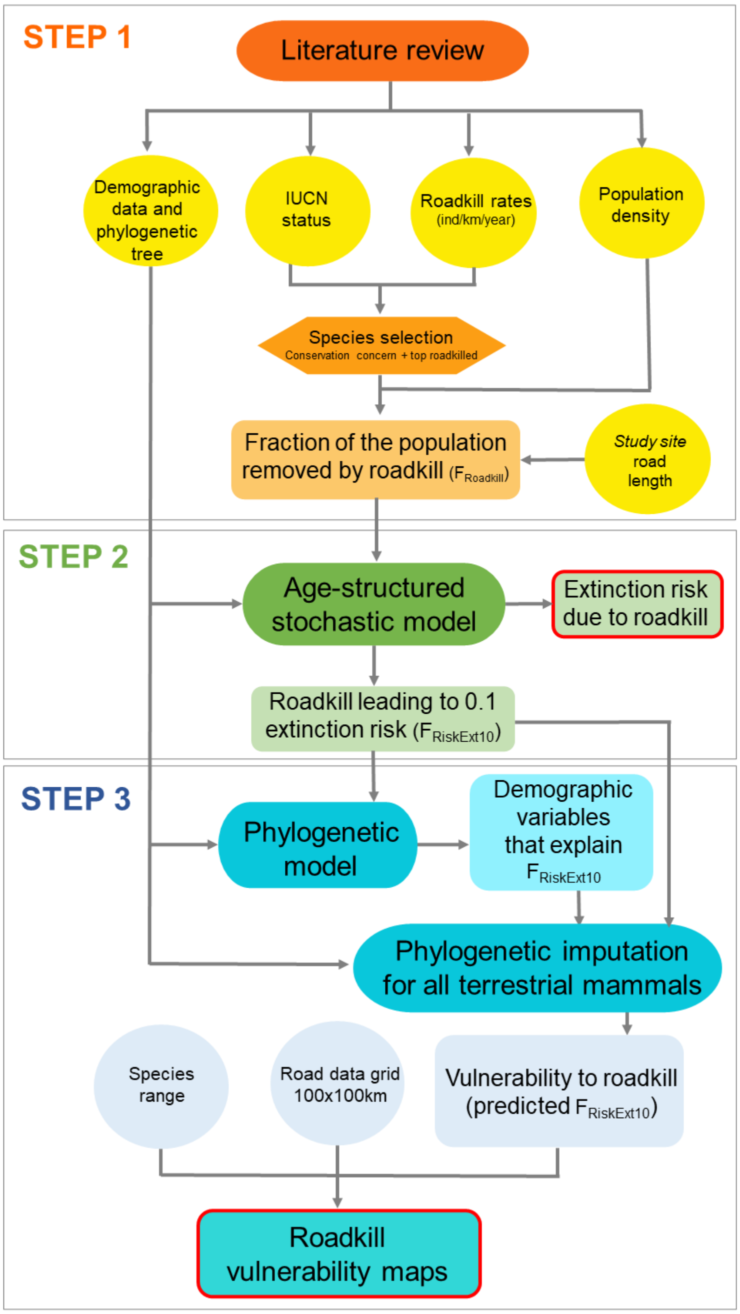

Figure 1 – Our proposed framework to quantify roadkill impacts on mammals worldwide. The framework includes three steps: step 1 - roadkill rates and estimated fraction of the population roadkilled per year; step 2 – risk of extinction from roadkill for the selected species, and step 3 -global assessment of mammal species vulnerability to roadkill. The two boxes framed in red are the main outputs.

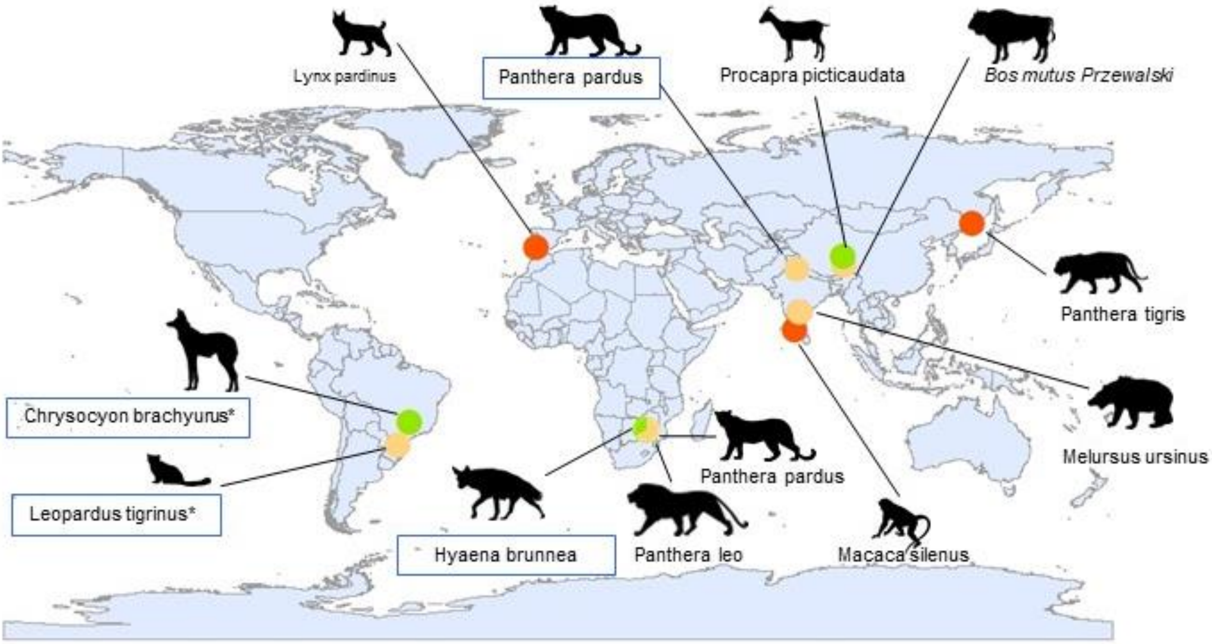

Figure 2 – Location of the species most vulnerable to roadkill ($F_{RiskExt10}$ <0.2). The scientific names framed in blue are those for which observed roadkill are estimated to lead to higher risk of extinction in 50 years if the observed roadkill persist in the region. Coloured dots are the IUCN status (Endangered – orange; Vulnerable – yellow, Near Threatened – green; Asterisks indicate species with intermediate vulnerability to roadkill (0.2<$F_{RiskExt10}$ <0.5) (SM1 and SM6). Mammal species silhouettes from PhyloPic (http://phylopic.org).

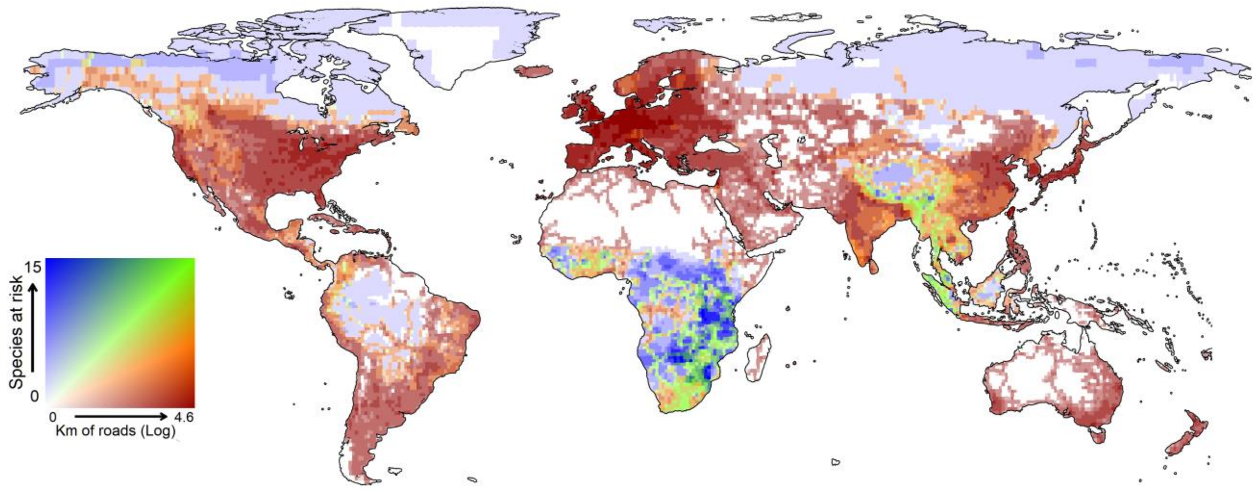

Figure 3 – Global distribution of the overlap between vulnerable species (mammal species for which roadkill of <20% of their population can lead to an additional 0.1 probability of extinction) and current paved road density (as $\log_{10}$ kilometres of road per 100-km x100-km grid cell). Green areas indicate "hot spots" of risk and exposure, blue areas represent "opportunities" for conservation with species at risk but current low road densities, brown areas are "humanized" with high road densities and few species at risk, light purple areas have both low road densities and no vulnerable species. White colour indicate no threatened species and no roads.

Data accessibility

The full database of roadkill and biological traits, age structured model R scripts and outputs are available as supporting information.

A short title for each numbered item in the supplementary material:

SM1 - List of species with roadkill and references
SM2 - Biological traits for the selected species and references
SM3 - Spatial implicit age-structured stochastic models
SM4 - Identifying species potentially threatened by roadkill
SM5 - Risk of extinction when the fraction of the population is removed due to observed roadkill for four species' populations
SM6 - Results from the spatially implicit age-structured stochastic models
SM7 - Qualitative validation of results from the spatially-implicit age-structured stochastic models for species predicted to be most ($F_{RiskExt10}$ <0.20) and least vulnerable ($F_{RiskExt10}$ >0.90)
SM8 - Relative importance of each variable from GLS and PGLS model sets and averaged model coefficients with confidence intervals for each variable
SM9 - Vulnerable species to roadkill

Appendix S9

Vulnerable species to roadkill

Data, results of imputation and validation

Table S9.1 - 124 species in ascending order from $F_{RiskExt10}$ <0.20

Species	$F_{RiskExt10}$
Bos mutus	0.070
Redunca redunca	0.072
Loxodonta africana	0.075
Loxodonta cyclotis	0.075
Panthera tigris	0.080
Bos grunniens	0.086
Elephas maximus	0.086
Helarctos malayanus	0.087
Syncerus caffer	0.088
Dicerorhinus sumatrensis	0.089
Rhinoceros unicornis	0.105
Pan troglodytes	0.106
Pan paniscus	0.110
Giraffa camelopardalis	0.117
Homo sapiens	0.118
Ceratotherium simum	0.119
Hexaprotodon liberiensis	0.123
Diceros bicornis	0.125
Gorilla beringei	0.128
Pongo abelii	0.128
Pongo pygmaeus	0.128
Ursus maritimus	0.129
Hippopotamus amphibius	0.130
Bison bonasus	0.132
Gorilla gorilla	0.135
Ailuropoda melanoleuca	0.139
Bos sauveli	0.141
Rhinoceros sondaicus	0.141
Bunopithecus hoolock	0.142
Ovibos moschatus	0.143
Equus grevyi	0.146
Panthera onca	0.146
Camelus bactrianus	0.147
Tragelaphus eurycerus	0.147
Hylobates klossii	0.147
Nomascus gabriellae	0.147

Nomascus siki	0.147
Melursus ursinus	0.150
Indri indri	0.151
Capricornis crispus	0.151
Capricornis swinhoei	0.151
Bubalus mindorensis	0.154
Brachyteles arachnoides	0.155
Brachyteles hypoxanthus	0.155
Hylobates agilis	0.157
Hylobates albibarbis	0.157
Hylobates moloch	0.157
Hylobates lar	0.159
Hylobates muelleri	0.159
Ateles geoffroyi	0.161
Redunca arundinum	0.162
Symphalangus syndactylus	0.162
Bos javanicus	0.163
Nomascus leucogenys	0.163
Lagothrix cana	0.165
Lagothrix lagotricha	0.165
Lagothrix lugens	0.165
Lagothrix poeppigii	0.165
Taurotragus derbianus	0.166
Mazama gouazoubira	0.166
Addax nasomaculatus	0.166
Tremarctos ornatus	0.166
Camelus dromedarius	0.167
Nomascus hainanus	0.167
Capra caucasica	0.167
Naemorhedus baileyi	0.169
Naemorhedus caudatus	0.169
Naemorhedus goral	0.169
Naemorhedus griseus	0.169
Hylobates pileatus	0.169
Capra nubiana	0.169
Beatragus hunteri	0.170
Bubalus quarlesi	0.170
Hyaena brunnea	0.170
Macaca silenus	0.170
Panthera leo	0.170
Kobus leche	0.171
Capra walie	0.171
Bos taurus	0.171
Bubalus depressicornis	0.171

Damaliscus korrigum	0.172
Damaliscus lunatus	0.172
Capricornis milneedwardsii	0.173
Capricornis rubidus	0.173
Capricornis sumatraensis	0.173
Capricornis thar	0.173
Bos frontalis	0.174
Nomascus concolor	0.174
Capra ibex	0.176
Equus hemionus	0.177
Tapirus indicus	0.178
Capra sibirica	0.178
Okapia johnstoni	0.178
Equus kiang	0.180
Tragelaphus buxtoni	0.181
Equus zebra	0.181
Connochaetes gnou	0.181
Ursus arctos	0.183
Ateles belzebuth	0.185
Ateles hybridus	0.185
Ateles marginatus	0.185
Hippotragus niger	0.186
Budorcas taxicolor	0.188
Rucervus duvaucelii	0.189
Hemitragus jayakari	0.189
Cebus olivaceus	0.190
Lynx pardinus	0.190
Procapra picticaudata	0.190
Kobus megaceros	0.190
Lophocebus albigena	0.191
Lophocebus aterrimus	0.191
Lophocebus opdenboschi	0.191
Hemitragus jemlahicus	0.192
Ovis nivicola	0.194
Equus burchellii	0.195
Alcelaphus buselaphus	0.195
Alcelaphus caama	0.195
Taurotragus oryx	0.195
Ateles fusciceps	0.195
Ursus americanus	0.196
Kobus ellipsiprymnus	0.196
Rangifer tarandus	0.197
Ovis canadensis	0.199
Cercocebus galeritus	0.199

Imputation LOOCVdata.csv

Complete list of species vulnerability (Imputation LOOCVresults.csv)

At 10.6084/m9.figshare.12993470

Data and results of the imputation of $F_{RiskExt10}$ (mean, lower confidence interval and upper confidence interval for age of maturity, litter size and litter per year and $F_{RiskExt10}$ for all 4677 species).

Validation LOOCVresults.csv

At 10.6084/m9.figshare.12993470 (*The DOI becomes active upon publication*).

Validation of phylogenetic imputation using Leave-One-Out Cross-Validation (LOO-CV)

Validation of phylogenetic imputation using Cross-Validation

Leave-one-out cross-validation (LOO-CV) was performed in Rphylopars using the methods described by Bruggeman (2009). Briefly, the Rphylopars trait evolutionary model was used to impute $\mathbf{F_{RiskExt10}}$ risk for all species on the phylogeny in which this $\mathbf{F_{RiskExt10}}$ was not "observed" (i.e. $\mathbf{F_{RiskExt10}}$ estimates were unavailable). For LOO-CV, each observed $\mathbf{F_{RiskExt10}}$ value was iteratively dropped from the model individually, and the original model parameters were used to impute each suppressed observation. Results from LOO-CV revealed a strong correlation (R^2=0.69) between observed $\mathbf{F_{RiskExt10}}$ risk and imputed, suggesting phylogeny-wide extrapolation of $\mathbf{F_{RiskExt10}}$ risk provides reliable results (Figure S8.1). Average bias (the difference between estimated and observed values) was -0.01%, and the root mean squared error (RMSE) was 15.5%.

To obtain species-level (and clade-level) estimates of expected error and bias, observed model errors and biases were phylogenetically reconstructed in Rphylopars and themselves subjected to LOO-CV. Results suggest species- and clade-level estimates of bias and error are also quite reliable (R^2=0.73 and R^2=0.86, respectively) (Figure S8.2 and S8.3). The final estimates of bias and error are presented in columns $F_{RiskExt10\ bias\ (adjusted)}$ and $F_{RiskExt10\ bias\ (adjusted)}$ (SM10LOOCVresults.csv their slopes and intercepts are corrected based on the relationship between observed and predicted bias and error) from LOO-CV results (raw results and intermediate calculations can be found in SM10LOOCVdata.csv). The species contained within each clade are listed in columns species_in_clade (and species_continued_1 and species_continued_2 when Excel cell length was exceeded).

LOO-CV may potentially underestimate error in the presence of structured data, so we performed 2-fold and 5-fold cross-validation blocked by phylogenetic distance to further validate our results (Roberts et al. 2017). Results were consistent with LOO-CV, with 2-fold and 5-fold cross-validations resulting in mean biases of 1.9% and 0.8% respectively (vs -0.01% for LOO-CV), and RMSE of 15.5% and 14.7% respectively (vs 15.5% for LOO-CV).

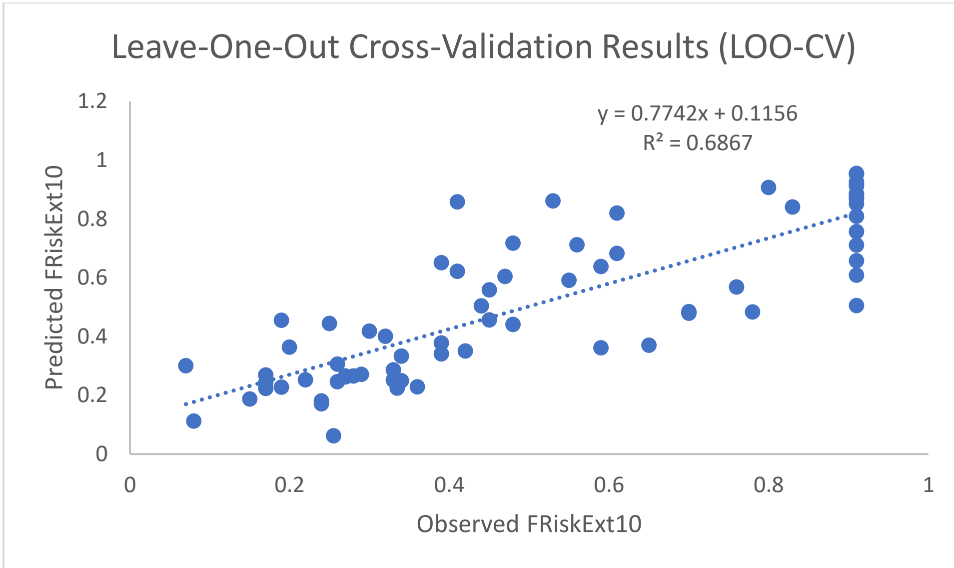

Figure S9.1 – Correlation between predicted and observed $\mathbf{F}_{\mathbf{RiskExt10}}$.

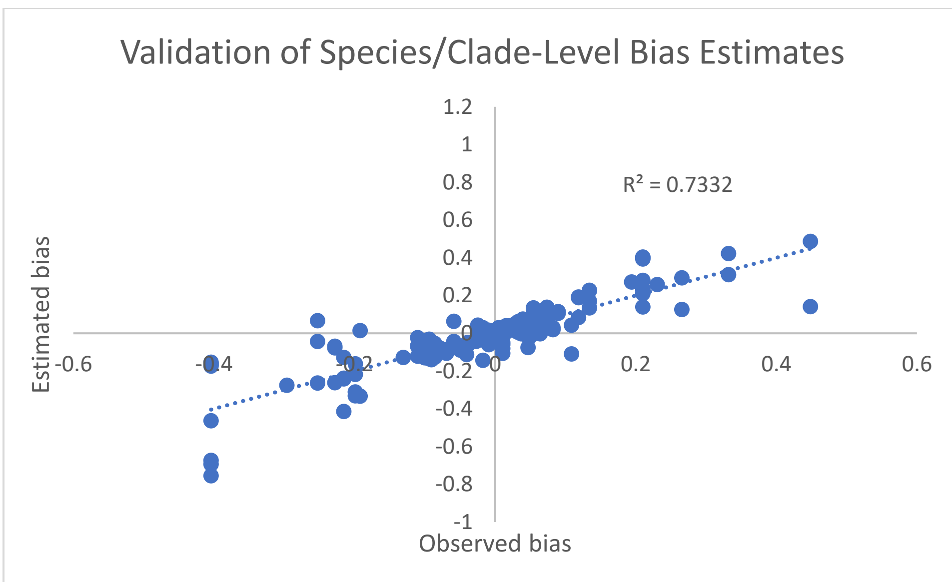

Figure S9.2 - Correlation between estimated and observed bias.

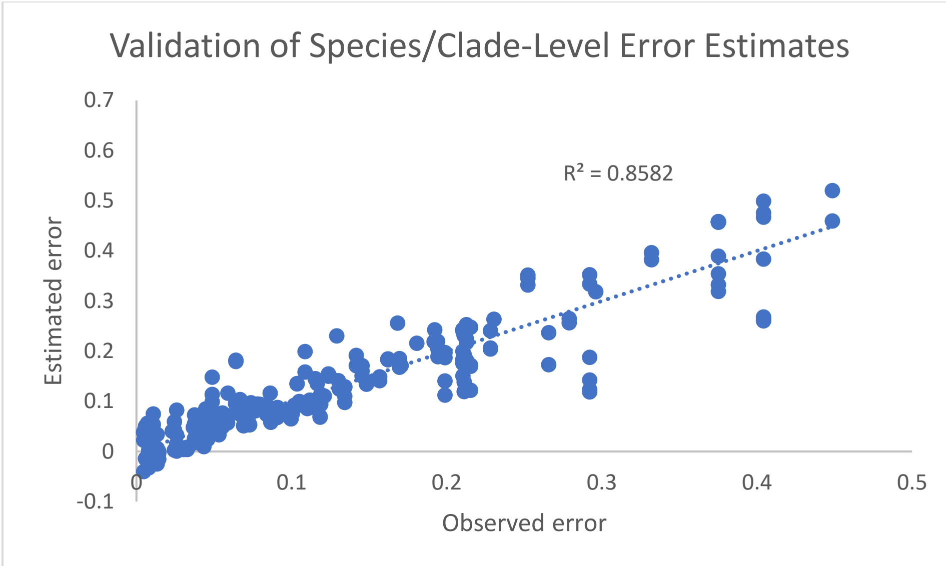

Figure S9.3 - Correlation between estimated and observed error.

Files used to prepare Figure 3

At 10.6084/m9.figshare.12993470

SHAPEFILES

LandoutlineCEA2 – Outline of the world map

GridCEALand - shapefile with one polygon for each of the terrestrial grids used in the analyses. The unique identified for each cell grid (to match with other files) is PageNumber

GridMammalsCEA - shapefile with data for each of the terrestrial mammals overlapping each terrestrial grid described in GridCEALand. This file was used to calculate grid statistics presented below.

CSV FILES

RoadlengthGrid.csv – sum of all paved roads in each cell grid. The unique identified for each cell grid (to match with other files) is PageNumber.

GridStats.csv - summary statistics for each grid cell described in GridCEALand shapefile.

Metadata – description of all steps to prepare Figure 3.

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Appendix S8

Relative importance of each variable from GLS and PGLS model sets and averaged model coefficients with confidence intervals for each variable

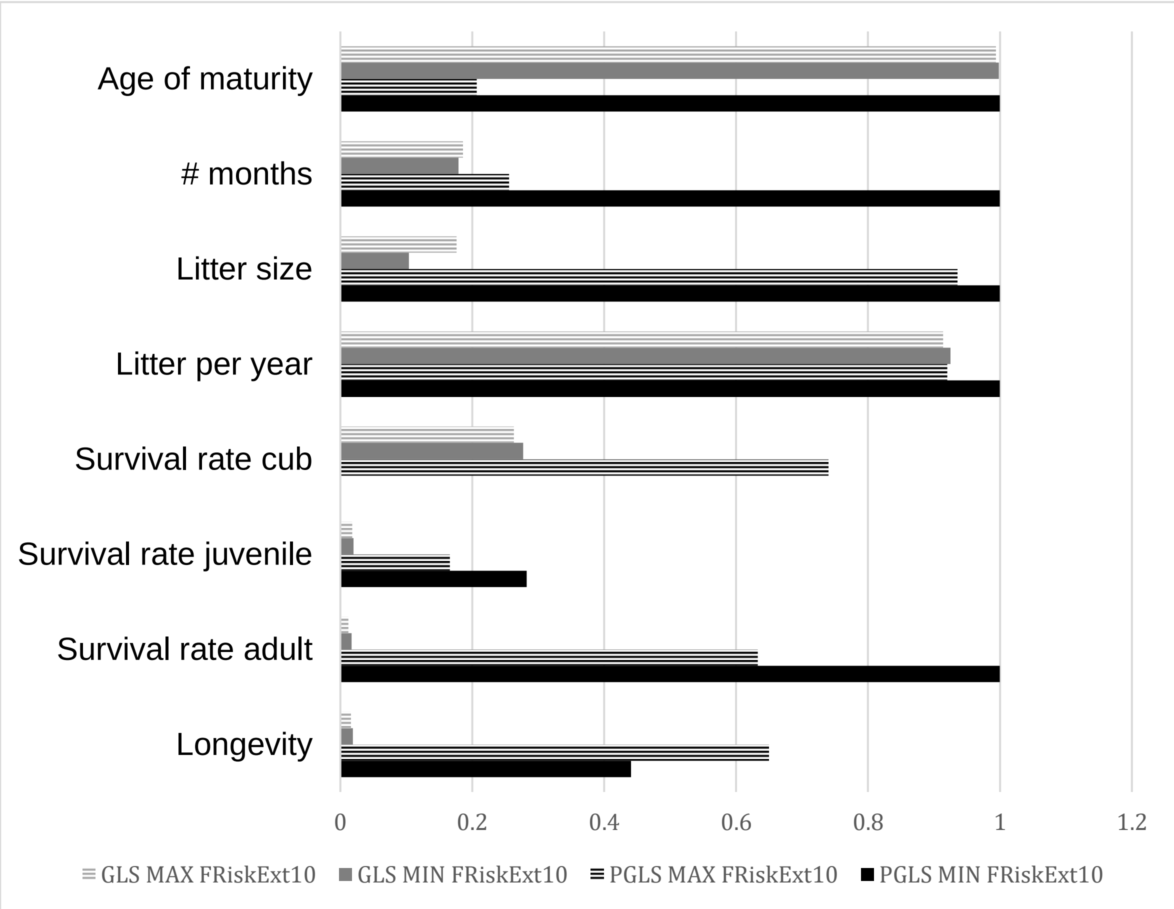
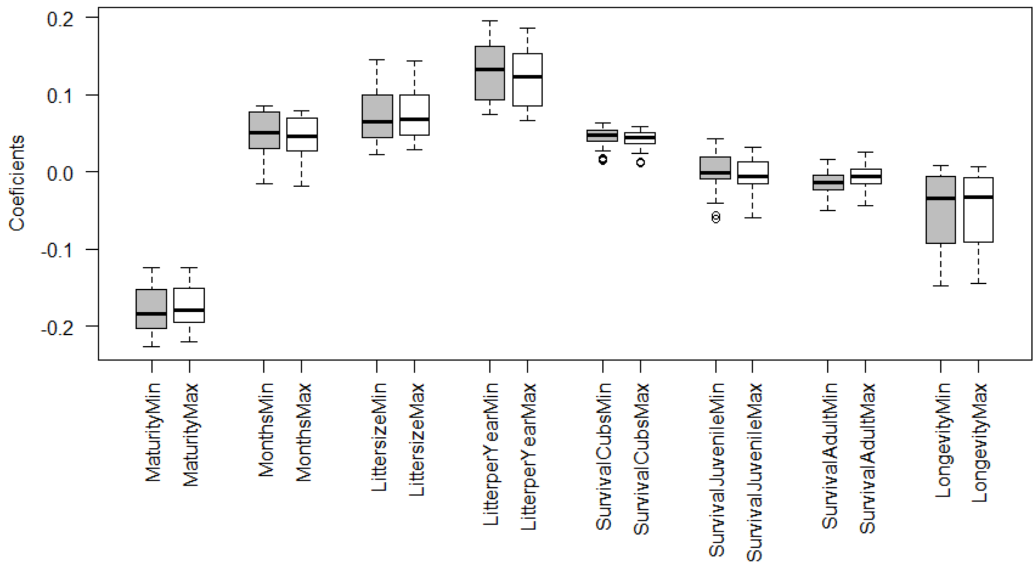


Figure S8.1 – Relative importance of each variable (age of maturity, # months - number of months of recruitment, litter size, number of litters per year, survival rates for cubs, juveniles and adults and longevity) calculated as the sum of Akaike weights for GLS and PGLS model sets using the Maximum and Minimum $F_{RiskExt10}$ (GLS MAX FRiskExt10, GLS MIN FRiskExt10, PGLS MAXFRiskExt10 and PGLS MINFRiskExt10).

GLS



PGLS

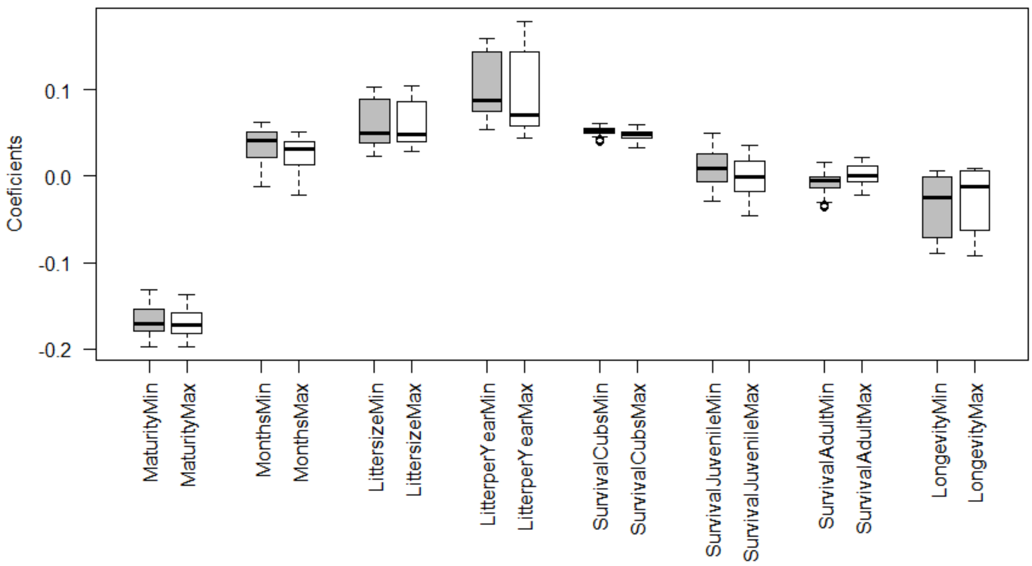


Figure S8.2 - Averaged model coefficients with confidence intervals of each variable for GLS and PGLS model sets with Minimum and Maximum $F_{RiskExt10}$ (example: MaturityMin, MaturityMax, respectively).

APPENDIX S7

Table S7.1 - Qualitative validation of results from the spatially-implicit age-structured stochastic models for species predicted to be most ($F_{RiskExt10}$ <0.20) and least vulnerable ($F_{RiskExt10}$ >0.90). We searched the literature to identify studies that showed increased risk of extinction from anthropogenic mortality (roadkill or another source). Data includes: species (scientific name), $F_{RiskExt10}$, reference for those species for which we identified evidence of vulnerability towards roadkill or other human-induced mortality.

Species	$F_{RiskExt10}$	Reference
Most vulnerable		
Panthera pardus	0.03-0.18	Ceia-Hasse et al. 2017
Panthera tigris altaica	0.06-0.12	Tian et al. 2011
Bos mutus Przewalski	0.10-0.11	
Lynx pardinus	0.11-0.46	Ceia-Hasse et al. 2017; Ferreras et al 2001
Melursus ursinus	0.14-0.16	Ceia-Hasse et al. 2017
Panthera leo	0.15-0.25	Snyman et al. 2015
Hyaena brunnea	0.15-0.26	
Macaca silenus	0.17	
Procapra picticaudata	0.19-0.20	
Least vulnerable		
Apodemus sylvaticus	>0.90	
Atelerix albiventris	>0.90	
Cavia aperea	>0.90	
Didelphis virginiana	>0.90	
Microtus mexicanus	>0.90	
Myodes rufocanus	>0.90	
Neofiber alleni	>0.90	
Ondatra zibethicus	>0.90	
Oryctolagus cuniculus	>0.90	
Otomys irroratus	>0.90	
Perameles gunnii	>0.90	Todd et al. 2001*
Perameles nasuta	>0.90	
Sylvilagus bachmani	>0.90	
Vulpes vulpes	>0.90	Ceia-Hasse et al. 2017
Xerus inauris	>0.90	

*not actual mortality but removal for translocations

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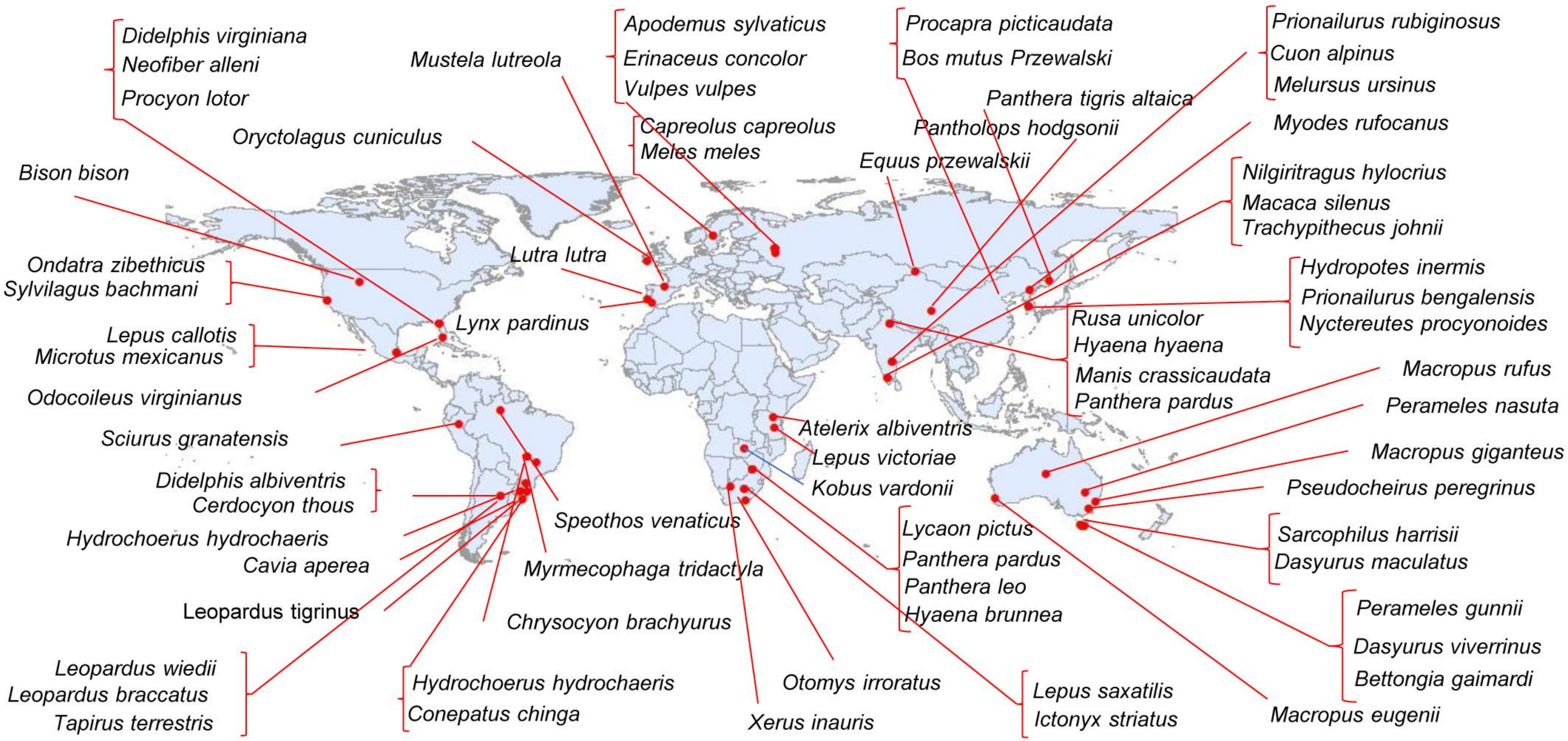
Appendix S6

Table S6.1 Results from the spatially implicit age-structured stochastic models - species, IUCN (IUCN status) $F_{roadkill}$ (fraction of the population roadkilled), reduction (population reduction - %), probability of extinction (%), Time to extinction (years), $F_{RiskExt10}$ (fraction of the population roadkilled that leads to an increase in 10% of risk of extinction - minimum and maximum found for the 12 carrying capacities).

Species	IUCN	$F_{roadkill}$	Reduction (%)	Probability of extinction (%)	Time to extinction (years)	$F_{RiskExt10}$
North America						
Microtus mexicanus	VU	0.00002	<1	0	-	>0.90
Bison bison	NT	0.004	<20	0	-	0.25-0.26
Lepus callotis	NT	0.007	4	0	-	0.60-0.63
Procyon lotor	LC	0.01-0.05	4-19	0	-	0.69-0.70
Ondatra zibethicus	LC	0.26	25	0	-	>0.90
Neofiber alleni	LC	0.006	<2	0	-	>0.90
Sylvilagus bachmani	LC	0.09	12	0	-	>0.90
Odocoileus virginianus	LC	0.14	77	0	-	0.29-0.31
Didelphis virginiana	LC	0.234	24	0	-	>0.90
South America						
Leopardus tigrinus	VU	0.20-0.37	66-98	0-75	0-36	0.32-0.33
Myrmecophaga tridactyla	VU	0.023-0.24	22-94	0	-	0.27-0.28
Tapirus terrestris	VU	0.003-0.015	<23	0	-	0.26-0.28
Chrysocyon brachyurus	NT	0.364	94	34	30	0.28-0.29
Leopardus wiedii	NT	0.04-0.19	21-70	0	-	0.36-0.39
Speothos venaticus	NT	0.0115	4	0	-	0.67-0.71
Leopardus braccatus	NT	0.01-0.08	3-25	0	-	0.38-0.39
Cavia aperea	LC	<0.001	<1	0	-	>0.90
Didelphis albiventris	LC	0.25	82	0	-	0.40-0.42
Sciurus granatensis	LC	0.01	3	0	-	0.81-0.85
Hydrochoerus hydrochaeris	LC	0.001-0.005	<1	0	-	0.47-0.48
Cerdocyon thous	LC	0.09	44	0	-	0.4-0.42
Conepatus chinga	LC	0.04	14	0	-	0.59-0.62
Europe						
Mustela lutreola	CR	0.007	<4	0	-	0.43-0.49
Lynx pardinus	EN	0.12	49	0	-	0.11-0.46
Oryctolagus cuniculus	NT	0.0008	5	0	-	>0.90
Lutra lutra	NT	0.09	32	0	-	0.39-0.40
Meles meles	LC	0.09	52	0	-	0.44-0.45
Erinaceus concolor	LC	0.18-0.34	62-87	0	-	0.52-0.53
Apodemus sylvaticus	LC	0.27	27	0	-	>0.90
Vulpes vulpes	LC	0.09	19	0	-	>0.90
Capreolus capreolus	LC	0.16	72	0	-	0.41-0.43
Africa						
Lycaon pictus	EN	0.01	7	0	-	0.33-0.34
Panthera pardus	VU	0.001-0.002	<10	0	-	0.03-0.18
Panthera leo	VU	0.004-0.009	<15	0	-	0.15-0.25
Kobus vardonii	NT	0.00007	<8	0	-	0.26-0.29
Hyaena brunnea	NT	0.06-0.43	40-100	3-100	0-21	0.15-0.26
Lepus saxatilis	LC	0.01	4	0	-	0.69-0.71
Lepus victoriae	LC	0.0009	<0.5	0	-	0.89-0.90

Species	IUCN	$F_{roadkill}$	Reduction (%)	Probability of extinction (%)	Time to extinction (years)	$F_{RiskExt10}$
Atelerix albiventris	LC	0.03	10	0	-	>0.90
Ictonyx striatus	LC	0.07	38	0	-	0.48
Xerus inauris	LC	0.0001	<3	0	-	>0.90
Otomys irroratus	LC	0.28	29	0	-	>0.90
Asia						
Panthera tigris altaica	EN	0.004	<15	0	-	0.06-0.12
Nilgiritragus hylocrius	EN	0.0003	0.4	0	-	0.26-0.27
Cuon alpinus	EN	0.0003	<14	0	-	0.20-0.21
Manis crassicaudata	EN	0.001	<5	0	-	0.27-0.28
Macaca silenus	EN	0.001	<8	0	-	0.17
Pantholops hodgsonii	EN	0.0007	<7.6	0	-	0.28-0.29
Equus przewalskii	EN	0.05	27	0	-	0.21-0.23
Trachypithecus johnii	VU	0.00004	<13	0	-	0.33-0.34
Prionailurus rubiginosus	VU	0.0002	<2	0	-	0.65-0.66
Melursus ursinus	VU	0.001	<11	0		0.14-0.16
Hydropotes inermis	VU	0.07	<31	0	-	0.54-0.56
Bos mutus Przewalski	VU	0.0007	<14	0	-	0.10-0.11
Rusa unicolor	VU	0.0014	<8	0	-	0.33-0.34
Panthera pardus	VU	0.194	99	83	33	0.03-0.18
Hyaena hyaena	NT	0.008	6.7	0	-	0.36
Procapra picticaudata	NT	0.006	<0.001	0	-	0.19-0.2
Myodes rufocanus	LC	0.001	<0.9	0	-	>0.90
Prionailurus bengalensis	LC	0.07	33	0	-	0.51-0.52
Nyctereutes procyonoides	LC	0.006	<2	0	-	0.54-0.57
Oceania						
Sarcophilus harrisii	EN	0.0022	<7	0	-	0.29-0.34
Perameles gunnii	NT	0.0001	<2.4	0	-	>0.90
Bettongia gaimardi	NT	0.035	4	0	-	0.76-0.77
Dasyurus viverrinus	NT	0.0003	<3	0	-	0.73-0.75
Dasyurus maculatus	NT	0.0001	9.7	0	-	0.36-0.40
Macropus eugenii	LC	0.23	77	0	-	0.43-0.46
Macropus giganteus	LC	0.014	19	0	-	0.25-0.26
Macropus rufus	LC	0.07	13	0	-	0.59-0.60
Perameles nasuta	LC	0.005	<1	0	-	>0.90
Pseudocheirus peregrinus	LC	0.04	17	0	-	0.59-0.60

Figure S6.1 Location of the populations analysed with spatially implicit age-structured stochastic models.



Appendix S5

Risk of extinction when the fraction of the population is removed due to observed roadkill for four species' populations (maned wolf, little spotted cat, brown hyena and leopard).

Maned wolf with an estimated roadkill rate of 0.08 ind/km/year (Carvalho 2014) and a population density of 0.038 ind/km/year has a 34% of risk of extinction.

Little spotted cat with a road roadkill rate of 0.09 ind./km/year (Marocco et al. 2012) and a population density that can vary between 0.07 and 0.13 ind./km^2 has a probability of extinction that ranges from 0% to 75%.

The risk of extinction of **brown hyena** with a roadkill rate of 0.03 ind./km/year (Collinson et al. 2015) and an observed population density that varies between 0.005 and 0.04 ind./km^2 (Boast et al 2011; Welch et al 2015) is between 3 and 100%.

Leopard with a roadkill rate of 0.052 ind/km/year (Joshi 2012) and a population density of 0.042 (Borah et al. 2014) has an 83% risk of extinction.

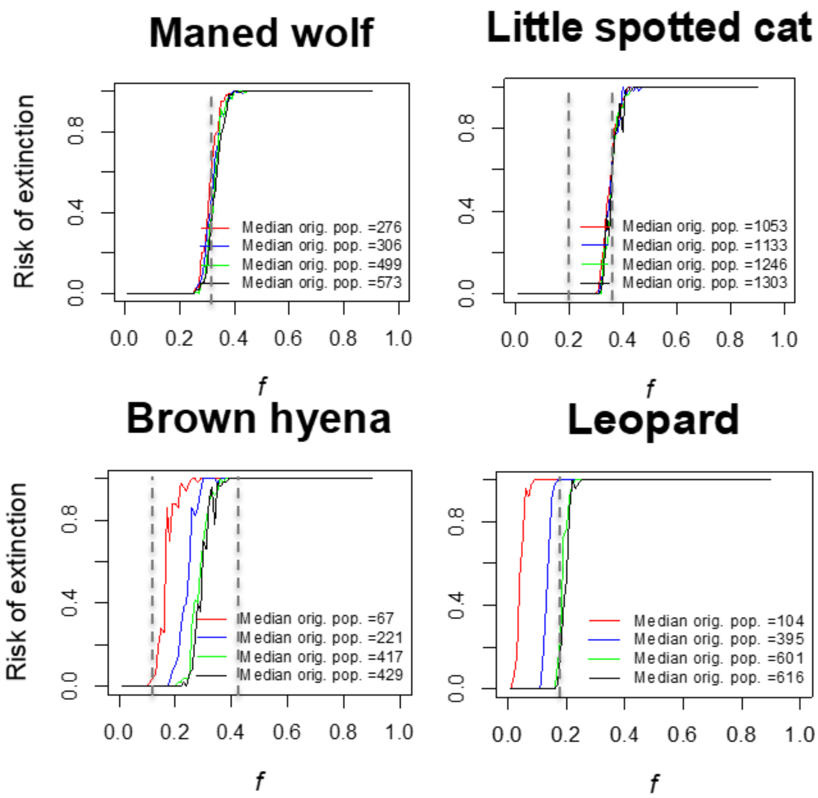


Figure S5.1 – Risk of extinction when a fraction *f* of the population is removed for four species populations (maned wolf, little spotted cat, brown hyena and leopard) under threat with the observed roadkill rates. Dashed lines in grey are the observed fractions of the population. The different colours correspond to simulations of different median sizes of the population before application of road mortality.

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Appendix S4

Identifying species potentially threatened by roadkill

We considered mammalian species potentially threatened by roadkill (those species where removal of <20% of their population may lead to an additional 10% risk of extinction).

We performed this task in four steps:

1 - Relationship between $F_{RiskExt10}$ and the demographic parameters

We used two approaches to analyse the relationship between $F_{RiskExt10}$ (population needed to be roadkilled to increase in 10% the risk extinction) and the demographic parameters:

1) non-phylogenetic least square regression (GLS) which assumes all species values are independent;
2) phylogenetic GLS (PGLS) which controls for lack of independence due to evolutionary relationships among species.

$F_{RiskExt10}$ (SM7) was the variable response and the predictor variables were: age of maturity (Myhrvold et al. 2015), number of months of recruitment, litter size, number of litters per year, survival rates in cubs, juveniles and adults, and longevity (SM4). We ran four models with the minimum and maximum values of $F_{RiskExt10}$ for GLS and PGLS analysis (MIN $F_{RiskExt10}$ and MAX $F_{RiskExt10}$ for GLS and PGLS) (SM6).

Firstly, we investigated correlations among demographic parameters (r>0.7; Zuur et al. 2009) and variable inflation factors (VIF) for all parameters (VIF>3; Zuur et al. 2009). Parameters were standardized and fitted to a global GLS model. We ran all possible combinations of demographic parameters. We also fitted a global PGLS and ran all combinations with the same demographic parameters to account for interdependence between species resulting from common evolutionary history. We used a phylogenetic tree of the mammal species obtained from the time tree (http://www.timetree.org). We measured the strength of phylogenetic signal in each variable by estimating the phylogenetic correlation between species based on Pagel's λ (Pagel 1999). Values of λ can vary continuously from 0 (indicating demographic parameters are independent of phylogeny) to 1 (indicating demographic parameters of species evolved under the Brownian motion model). We found that values λ for the parameters ranged from 0.41 to 0.80, thus indicating accounting for phylogeny is warranted (Revell 2010). We therefore controlled for the degree of phylogenetic non-independence in our analysis. We analysed the relative importance of each variable calculated as the sum of Akaike weights for GLS and PGLS models. All analysis were performed with R 3.4 (R development Core team 2014-2016). Phylogenetic analysis was conducted with the *ape, phytools* (Revell 2012) and *geiger* (Harmon et al. 2008) R packages. For six species not included in the phylogenetic tree (*Didelphis albiventris, Kobus vardonii, Lepus microtis, Manis crassicuadata, Nilgiritragus hylocrius* and *Prcapra picticaudata*) we substituted other species of the same genus (*Didelphis imperfects, Kobus kob, Lepus europaeus, Manis javanica, Hemitragus jayakari* and *Procapra przewalskii),* respectively.

2 - Key demographic parameters that explain $F_{RiskExt10}$

We selected the key demographic variables that provided a very high contribution to explain the $F_{RiskExt10}$ for both GLS and PGLS models and for minimum and maximum $F_{RiskExt10}$ and were also well documented in the life traits database for 4664 mammal species (Myhrvold et al. 2015) to impute the fraction of the population removed due to roadkill needed to lead to 10% risk of local extinction for mammal species worldwide.

3 – Imputation of the $F_{RiskExt10}$ for mammal species worldwide using the key demographic parameters

We used age of maturity and number of litters per year (both variables were concordant for GLS and PGLS analysis) plus litter size (important variable in PGLS analysis) to impute the $\mathbf{F_{RiskExt10}}$ (SM6). In the life traits database 40% of species had age of maturity data, 71% had litter size and 43% had litter per year. We imputed 4664 unique species that matched traits (Myhrvold et al. 2015), phylogeny (Fritz et al. 2009) and IUCN species range maps (SM9).

We used the phylogenetic tree for the world mammal species (Fritz et al. 2009) for which the number of species matched to IUCN species range maps (downloaded from the IUCN Red List web site (http://www.iucnredlist.org/) and the *Rphylopars* R package (Goosbly et al. 2017) to estimate maximum likelihood trait covariance in light of phylogenetic relatedness assuming a Brownian motion model of trait evolution. The selected demographic parameters were log-transformed and $F_{RiskExt10}$ was logit-transformed prior to analyses. Branches for eight taxa (*Bos mutus*, *Equus przewalskii*, *Hydrochoerus hydrochaeris*, *Kobus vardonii*, *Panthera tigris altaica*, *Nilgiritragus hylocrius*, and *Lepus microtis*) were manually added as sister taxa to the most closely represented members of the phylogeny. Using the maximum likelihood trait covariance and expected species covariance due to shared ancestry, missing values for all variables were phylogenetically imputed, and the resulting imputations and 95% confidence intervals were de-transformed back to their original scale (SM8).

4 – Validation of phylogenetic imputation using Leave-One-Out Cross-Validation (LOO-CV)

Leave-one-out cross-validation (LOO-CV) as well as 2-fold and 5-fold cross-validation blocked by phylogenetic distance was performed to evaluate the reliability of $F_{RiskExt10}$ imputation results (Bruggeman 2009; Roberts et al. 2017). For LOO-CV, average bias was -0.01% and the root mean squared error (RMSE) was 15.5%. In other words, for any given imputation, we can expect our estimates to be off, on average, about +/- 15.5%, and our estimates appear to be unbiased (see SM10 for further details). We recovered similar results using 2-fold and 5-fold phylogenetically blocked cross-validation yielding mean bias of 1.9% and 0.8% and RMSE of 15.5% and 14.7%, respectively. See SM9 for further details.

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Appendix S3

Spatially implicit age-structured stochastic models

We modelled each of the selected species and *study site* with a spatially implicit age-structured stochastic model based on Borda-de-Água et al. (2014) in order to calculate the probability of local extinction risk in a period of 50 years given the fraction of the individuals removed from the population due to road mortality. This model considers age at maturity, interval between births, litter size, period of recruitment, number of litters per year and mortality rates (Borda-de-Água et al. 2014). Mortality, Z_a, consists of natural mortality, M_a, and road mortality, C_a; that is, $Z_a=M_a+C_a$. The subscript *a* was included to indicate that both forms of mortality can be age specific. A population is divided into *n* age classes (starting at 0, corresponding to animals in their first year, up to *n*-1, the last year a cohort survives). Each age class is further divided into 12 months. Thus, a population has *n*x12 cohorts whose information is kept in a matrix with 12 columns and *n* rows. An iteration corresponds to a month, and in each iteration the number of individuals in the population is updated according to the mortality rate of its age group. Thus, if the cohort of age *a* at month *m* has $N_{a,m}$ individuals at time t_1, at time $t_2= t_1 + 1$ the number of individuals is calculated as

$$N_{a,m}(t_2) = N_{a,m}(t_1)e^{-Z_a},$$

assuming that mortality has time units of "month".

For those cohorts that are mature, in some months of the year and with a given periodicity, females can give birth. The number of females that give birth is determined according to the input parameters, as well as the number of offspring per female. The total number of recruits, *R*, that enter the population is related to the total number of animals born, *B*, through the Beverton-Holt relationship,

$$R = \frac{\alpha B}{\beta + B},$$

where α and β are parameters to be estimated. The recruits enter the population then at position $N_{0,1}$ and will start involving as the remaining of the population in the next iteration. Notice that it is the Beverton-Holt relationship that introduces density dependence in the model. For simplicity, we have assumed $\alpha=\beta$. In order to determine the parameter α we use an iterative process until the population attains the expected average number of individuals without road mortality. We used empirical estimates of variance for demographic parameters if available or assumed a 10% variance when no estimates were provided. We run the model using 600 simulations for each species: (50 replicates *12 carrying capacities).

After the model is initiated with an arbitrary starting population size there is a period of transient dynamics. We found population size converged very rapidly (usually < 50 years, 600 iterations) to a dynamic equilibrium state. We run this equilibrium state for 170 years (8500 iterations) to generate baseline dynamics without road mortality (*Za*=*Ma*). Finally, we ran the model for another 50 years with added roadkill mortality (*Za*=*Ma*+*Ca*). We calculated the probability of extinction as the proportion of computer runs relative to their total number in which the population went extinct at the end of those 50 years.

This approach assumes that (i) roadkill rates would be constant over the time in the defined area; (ii) the demographic parameters obtained from populations from other regions are appropriate; and (iii) the population is not distributed in a source-sink or metapopulation configuration.
The present code allows modelling populations with a wide range of parameters, and with further small changes new features can be introduced in order to introduce more realism. The main limitation of the model is that it is space implicit. The development of such code is outside the scope of the present work and will be the object of future work (the code with an example at 10.6084/m9.figshare.12993470 - *the DOI becomes active upon publication*).

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Appendix S2

Table S2.1 - Biological traits for the selected species and references

	IUCN	Population density Ind./km2	Age of first birth (days)	Month of recruitment	Interval between births (days)	Litter size	Litter per year	Maximum longevity (m)	Survival rate of cubs	Survival rate of juveniles	Survival rate of adults
NORTH AMERICA											
Bison bison	NT	0.28	1095	March-June	399	0.98	1	396	0.467	0.50	0.99
		Jones et al. 2009	Jones et al. 2009	Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Fuller et al. 2007	Meagher 1973	
Lepus callotis	NT	3.83	365	June-October	42	2.48	3	89	0.5	F(0.1) M(0.41)	0.43
		Jones et al. 2009	Jones et al. 2009 for L americanus	Best & Henry 1993	Estimated from Myers et al. 2016 and Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Median from *Lepus* Jones et al. 2009	Rioja et al. 2011 for L. flavigularis	Farias 2004 for L. flavigularis	
Microtus mexicanus	VU	1483.67	45	Oct-Feb	30	2.33	4.5	18	0.823	0.823	0.823
		Jones et al. 2009	http://www.nsrl.ttu.edu/tmot1/micrmexi.htm	Hilton 1992	Arizona Game and Fish Department 2003	Jones et al. 2009	Estimated from www.nsrl.ttu.edu	Atanasov 2012	Conley 1976		
Procyon lotor	LC	55.6-250	427	March-Nov	365	3.06	1	252	0.585	0.93	0.681
		Smith & Engeman (2003); Twichel and Dill (1949)	Johnson 1970	Troyer et al. 2014	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Gehrt & Fritzell 1999		
Ondatra zibethicus	LC	75.85	365	March-May	30	6.55	2.45	120	0.750	0.12	0.38
		Messier et al 1990 Twichel and Dill (1949)	Jones et al. 2009	Errington 1943	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Virgl & Messier 1997	Ahlers et al 2010	Virgl & Messier 2000
Neofiber alleni	LC	14516	95	All year	42.5	2.33	4.5	120	0.195	0.195	0.195
		Jones et al. 2009	Birkenholz 1963	Myers et al. 2016	Birkenholz 1963	Jones et al. 2009	Jones et al. 2009	=Ondatra zibethicus	=juvenile	Lefebvre 1982	=juvenile
Sylvilagus bachmani	LC	568	154	Jan-June	29.5	3.35	4.5	72	0.825	0.825	0.2
		Jones et al. 2009	Myers et al. 2016	Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Lord 1961	= juvenil	Williams et al 2008	Bond et al 2001
Odocoileus virginianus	LC	50	463	May-July	304	1.57	1	276	0.47**	0.75***	0.72*#
		Lankester & Peterson 1996	Jones et al. 2009	Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Myers et al. 2016	Jones et al. 2009	Carstensen et al. 2009	Grovenburg et al 2012	F Grovenburg et al 2011/M Mcdonald et al 2011
Didelphis virginiana	LC	8.52	186	Feb- Sept	136.87	8.62	2	60	0.76	0.23	0.28
		Beatty et al. 2016	Jones et al. 2009	Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	*Julien-Laferriere & Atramentowicz 1990	O'Connell 1989 for D. marsupialis	
SOUTH AMERICA											
Chrysocyon brachyurus	NT	0.031	730	Oct-Dec	365	2	1	180	0.4	0.8	0.9
		Trolle et al. 2007	Paula et al. 2008	Myers et al. 2016	Myers et al. 2016	Jones et al. 2009	Eol 2016	Jones et al. 2009	Paula et al. 2008		
Leopardus wiedii	NT	0.05-0.25	730	All year	365	1	1	156	0.68	0.87	F(0.825);M(0.75)
		Oliveira et al. 2010 Oliveira 2011	Green 1991; Leyhausen 1990	Myers et al. 2016	Myers et al. 2016 similar to other cats	Oliveira 1998	Myers et al. 2016 similar to other cats	Myers et al. 2016	Haines2006 for *L. pardalis)*		
Speothos venaticus	NT	0.01	364	2 months/year	240	4	1.5	123	0.2	0.2	0.38
		DeMatteo & Loiselle 2008	Myers et al. 2016	DeMatteo et al. 2006	Jones et al. 2009	http://genomics.senescence.info/	Meyers et al. 2016	Myers et al. 2016	= *Vulpes Vulpes*		
Leopardus braccatus/colocolo	NT	0.1-0.78	780	April-July	365	2	1	108	0.68	0.87	F(0.825);M(0.75)
		Oliveira et al. 2010; Gardner et al. 2010	Nowell and Jackson 1996	Myers et al. 2016	Myers et al. 2016	Nowell and Jackson 1996	Myers et al. 2016	Nowell & Jackson 1996	Haines2006 for *L. pardalis)*		

	IUCN	Population density Ind./km2	Age of first birth (days)	Month of recruitment	Interval between births (days)	Litter size	Litter per year	Maximum longevity (m)	Survival rate of cubs	Survival rate of juveniles	Survival rate of adults
Myrmecophaga tridactyla	VU	0.21-2.2	1095	All year	270	1	1	312	0.5	0.9	0.9^{**}
		Fonseca et al. 1994; Miranda 2004	Miranda 2004	Myers et al. 2016	Myers et al. 2016	Jones et al. 2009	Miranda 2004	Jones et al. 2009	Miranda 2004		
Tapirus terrestris	VU	0.13-0.58	1287	All year	365	1	1	420	0.9	0.85	0.92
		Desbiez 2010; Trolle et al_2008	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Jones et al. 2009	Myers et al. 2016	Jones et al. 2009	Gatti et al 2011		
Leopardus tigrinus	VU	0.07-0.13	790	Nov-Feb	365	1.2	1	144	0.68	0.87	F(0.825);M(0.75)
		Oliveira-Santos 2012	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Oliveira & Cassaro 2005	Myers et al. 2016	Myers et al. 2016	Haines2006 for *L pardalis*		
Cavia aperea	LC	1806	97	Nov-Jun	60	2	4	36	0.58	0.8	0.8
		Jones et al. 2009	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Asher et al. 2004		
Didelphis albiventris	LC	4	378	July - March	180	7	2	20	0.191	0.52	0.962
		Streilein 1982	Myers et al. 2016	D' Andrea et al.1999	Myers et al. 2016	D' Andrea et al. 1999	Myers et al. 2016	Myers et al. 2016	Ferreira et al. 2013 for D.autira		
Sciurus granatensis	LC	79	455	Feb-Dec	150	1.9	2.5	84	0.745	0.745	0.745
		Jones et al. 2009	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Myers et al. 2016	Wauters et al. 1994 for S. vulgaris		
Hydrochoerus hydrochaeris	LC	170-700	690	All year	365	4	1	144	0.32	0.597	0.618
		Garcias & Bager 2009	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Alvarez et al. 2006	Mones & Ojasti 1986	Jones et al. 2009	Moreira et al 2013		
Cerdocyon thous	LC	3.54	330	Jan-Feb/ Oct-Nov	243	4	2	138	0.42	0.93	0.93
		Ginsberg & Macdonald 1990	Myers et al. 2016	Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Myers et al. 2016	Jones et al. 2009	Sillero-Zubiri et al. 2004 for Lycalopex fulvipes		
Conepatus chinga	LC	5	330	April-May	365	3.5	1	72	0.42	0.42	0.42
		IUCN/Cofré and Marquet 1999	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Reis et al.2006	Myers et al. 2016	Gehrt 2005 for M. mephitis		
EUROPE											
Mustela lutreola	CR	0.044	323	April-May	365	4.5	1	60	0.33^{++}-0.35^{+++}	0.33^{++}-0.52^{+++}	$0.33^{++-}0.50^{+++}$
		Palazon et al 2002	Myers et al. 2016	Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Mañas et al 2016	Bonesi et al. 2006 for Neovison vison Maran 2003 for relased minks		
Lynx pardinus	EN	0.12	365	March/April	365	3	0.8	156	0.475	0.4	0.8
		Simon et al. 2012	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Ferreras et al 2001		
Oryctolagus cuniculus	NT	357	121.66	Jan-June	29	5.24	4.5	216	0.32	0.59	0.89
		Jones et al. 2009	Jones et al. 2009	Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Tablado et al. 2012		
Lutra lutra	NT	0.125	960	Jan-March	365	3	1	144	0.6	0.4	0.3
		Quaglietta et al. 2015	Myers et al. 2016	Beja 1996	Jones et al. 2009	Beja 1996	Jones et al. 2009	Ruiz-Olmo1988	Ruiz-Olmo1998		
Meles meles	LC	0.66	730	Feb-May Aug-Oct	365	2.5	1.	120	0.4	0.76	0.75
		Seiler et al 2005 (pop)	Seiler et al 2004 (1992)	Myers et al. 2016	Jones et al. 2009	Seiler et al 2004 (1992)	Myers et al. 2016	Seiler et al 2004 (1992)	Seiler et al 2004 (1992)		
Erinaceus concolor	LC	32(median)-60 (max)	293	Jun-Nov	180	5.23	1.5	72	0.34	0.34	0.47
		Savarin 2009	Myers et al. 2016 E. europaeus	Myers et al. 2016 E. europaeus	Myers et al. 2016 E. europaeus	Jones et al. 2009	Jones et al. 2009	Myers et al. 2016 E. europaeus	Kristiansson 1990 for E. europaeus		
Apodemus sylvaticus	LC	550	85	March-Dec	41.28	5.16	3.75	52.8	0.60	0.60	0.60
		Unnsteinsdóttir 2014	Jones et al. 2009	Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Unnsteinsdóttir 2014		
Vulpes vulpes	LC	1.1	354	April-May	365	4.59	1	180	0.8	0.7	0.5
		Jones et al. 2009	Myers et al. 2016	http://www.nfws.org .uk	Jones et al. 2009	Jones et al. 2009	Myers et al. 2016	Jones et al. 2009	Sillero-Zubiri et al. 2004		

	IUCN	Population density Ind./km2	Age of first birth (days)	Month of recruitment	Interval between births (days)	Litter size	Litter per year	Maximum longevity (m)	Survival rate of cubs	Survival rate of juveniles	Survival rate of adults
Capreolus capreolus	LC	1.11	730	April-July	365	1.79	1	204	0.62 M (±0.074); 0.69 F (±0.077)	0.90 M (± 0.06); 0.89 F (±0.066)	0.90 M (±0.058); 0.97 F (0.029)
		Madsen et al 2002	Jones et al. 2009	Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Myers et al. 2016	Jones et al. 2009	Cobben et al 2009		
AFRICA											
Lycaon pictus	EN	0.015	927	March-Jul	355.7	1.6**	1	132	0.71*	0.691	0.725
		Creel & Creel 1996	Jones et al. 2009	Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Woodroffe 2011		
Hyaena brunnea	NT	0.005-0.04	1095	Aug-Nov	532.29	2.3	0.4	204	0.86	0.62	0.47
		Boast et al. 2011; Welch et al 2015	Jones et al. 2009	Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Myers et al. 2016	Jones et al. 2009	Mills 1981	Wagner 2006	Wagner 2006
Panthera pardus	VU	0.05-0.09	1147	All year-round	476.37	2.14	1	276	0.39	0.86	0.88
		Rosenblatt et al. 2016	Jones et al. 2009	Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Swanepoel et al. 2015		
Panthera leo	VU	0.04-0.10	1047	All year-round	730	2.75	2	360	0.66	0.83	0.89
		Rosenblatt et al .2014	Jones et al. 2009	Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Dolrenry 2013		
Kobus vardonii	NT	12.91	630	All year-round	365	1	1	204	0.67*	0.67	0.9(m); 0.95(f)
		Rduch 2013	Myers et al. 2016	Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Myers et al. 2016	Myers et al. 2016	Martin 2004		
Lepus saxatilis	LC	18.6	407	All Yeat-ear-round	90	1.52	5.35	30	0.375	0.375	0.37
		Munoz 2013	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Myers et al. 2016	Misiorowska & Wasilewski 2012 for released L.europaeus		
Lepus victoriae	LC	95	277	All year-round	91	1.56	4	144	0.375	0.37	0.37
		Jones et al. 2009	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Jones et al. 2009	Myers et al. 2016	http://www.awf.org/wildlife-conservation/african-hare	Misiorowska & Wasilewski 2012		
Atelerix albiventris	LC	31.8	119	Oct-March	182	3.98	1	136.8	0.7	0.7	0.8
		Smilar to E. erinaceus Jackson 2006	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Myers et al. 2016	http://hedgehogvalley.com/hhogbreeding.html	Similar to cubs	Warwick et al 2006 for E. erinaceus
Ictonyx striatus	LC	0.5	304	Sept-Dec	365	2.3	1	160	0.68	0.68	0.49
		Hendrichs 1972	Jones et al. 2009	Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Kristiansen et al. 2007 for Mustela putorius		
Xerus inauris	LC	0.5	345.5	All year-round	100	2.06	1	156	0.745	0.745	0.745
		Jakobson 2006	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	=Sciurus vulgaris		
Otomys irroratus	LC	3004	103	All year-round	73	1.65	3.75	36	0.59	0.13	0.13
		Jones et al. 2009	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Myers et al. 2016	Davis 1973		
ASIA											
Panthera tigris altaica	EN	0.03	1460	all year except 3 months	642	1.4	0.3	108	0.5	0.4	0.7
		Jones et al. 2009	Kerley et al. 2003				Myers et al. 2016	Myers et al. 2016	Kerley et al. 2003	Goodrich et al 2008	
Nilgiritragus hylocrius	EN	4.23	879	All year	180	1.5	2	42	0.48	0.34	0.2
		Rice et al 1988	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	http://nilgiritahrinfo.info/introduction.htm	Rice et al 1988		
Cuon alpinus	EN	0.55	426	Nov-March	365	0.82**	1	192	0.18	0.37	0.37
		Jones et al. 2009	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	http://genomics.senescence.info	Myers et al. 2016	=Nyctereutes procyonoides		

	IUCN	Population density Ind./km2	Age of first birth (days)	Month of recruitment	Interval between births (days)	Litter size	Litter per year	Maximum longevity (m)	Survival rate of cubs	Survival rate of juveniles	Survival rate of adults
Manis crassicaudata	EN	1.15	790	All year except May June	365	1	1	162	0.667	0.167	0.125
		Irshad et al. 2015	Dickman 1984	Pattnaik 2008	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Mohapatra & Panda 2014		
Macaca silenus	EN	1.01	1825	All year, except June	365	0.35	1	240	0.87	0.861	0.503
		Jones et al. 2009	Myers et al. 2016	Singh 2006	Myers et al. 2016	Singh 2006	Myers et al. 2016	Myers et al. 2016	Singh 2006	= Cercopithecus mitis Bronikowski et al 2016	
Pantholops hodgsonii	EN	0.33	738	Jun-Jul	365	1	1	96	0.50	0.33	0.98
		Liu 2009	Myers et al. 2016	Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Myers et al. 2016	Myers et al. 2016	Schaller 2006		
Equus przewalskii	EN	0.01	1460	April-May	365	1	1	240	0.75	0.75	0.69
		Wang, 2014	http://library.sandiegozoo.org	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Boyd & Hopt 1994	Chen et al. 2008, Meng et al 2009		
Trachypithecus johnii	VU	71	1690	All year	365	1	1	348	0.48	0.34	0.2
		Jones et al. 2009	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	=Nilgiritragus hylocrius		
Prionailurus rubiginosus	VU	0.66	365	All year	165	2.2	1	48	0.5	0.5	0.725
		Myers et al. 2016 for Prionailurus bengalensis	Myers et al. 2016	Myers et al. 2016	Similar to Leopard cat	Jones et al. 2009	Myers et al. 2016	=Prionailurus bengalensis	=Prionailurus bengalensis		
Melursus ursinus	VU	0.13	1293	Nov-Jan	1095	1.5	1.5	480*	0.75	0.75	0.75
		Jones et al. 2009	Myers et al. 2016	Yoganand 2005	Jones et al. 2009	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Joshi 2011		
Hydropotes inermis	VU	6.93	363	May-June	365	3	1	144	0.73*?	0.73	0.73*?
		Kim et al 2011	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Jones et al. 2009	Myers et al. 2016	Myers et al. 2016	Chen et al 2015		
Bos mutus Przewalski	VU	0.03	2825	June	730	1	1	300	0.48	0.34	0.205
		Schaller 1996	Myers et al. 2016	Leslie & Schaller 2009	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	= Nilgiritragus hylocrius		
Rusa unicolor	VU	4.89	788	Sept-Jan	365	1.5	1	317	0.49	0.79	0.845
		Jones et al. 2009	Jones et al. 2009	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Jones et al. 2009	Leslie et al. 2010		
Panthera pardus	NT	0.042	1034	Year-round	600	2	1	102	0.39±0.1	0.80±0.12(M);0.93±0.07 (F)	0.94±0.04(M);0.86 ±0.05 (F)
		Borah et al. 2014	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Swanepoel et al. 2015		
Hyaena hyaena	NT	0.152	890	All year	455	2.44	1	288	0.96	0.89	0.545
		Gupta et al 2009	Myers et al. 2016	http://www.hyaenidae.org/	Myers et al. 2016	Jones et al. 2009	Myers et al. 2016	Jones et al. 2009	Bothma & Walker 1999	Wagner 2006	
Procapra picticaudata	NT	0.08	1520	June-July	365	1	1	96	0.48	0.34	0.205
		Bhatnagar et al. 2007	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	= Nilgiritragus hylocrius		
Myodes rufocanus	LC	465.17	110	All year	32.6	5.01	3	24	0.52	0.42	0.53
		Boonstra & Krebs 2012	Jones et al. 2009	Eol 2016	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Myers et al. 2016for M. rutilus	average estimated for all cricetidae		
Prionailurus bengalensis	LC	9.6	612	All year	165	2.5	1	48	0.5	0.5	0.725
		Mohamed et al. 2013	Myers et al. 2016	Myers et al. 2016	Jones et al. 2009	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Haines et al 2004		
Nyctereutes procyonoides	LC	86	361	March-May	365	6.33	1	90	0.18	0.37	0.37
		Myers et al. 2016/ Kauhala, et al. 1993	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Myers et al. 2016	Kowalczyk et al 2009		
OCEANIA											
Sarcophilus harrisii	EN	5.9	730	April	365	2.88	1	72	0.45*	0.45	0.55
		Jones et al. 2009	Jackson 2007	Jackson 2007	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Jones et al 2008	Lachish et al 2007		

	IUCN	Population density Ind./km2	Age of first birth (days)	Month of recruitment	Interval between births (days)	Litter size	Litter per year	Maximum longevity (m)	Survival rate of cubs	Survival rate of juveniles	Survival rate of adults
Perameles gunnii	NT	35	107.64	January (all)	65	2.31	3.8	66	0.53	0.74	0.76
		Mallick et al. 2000	Jones et al. 2009	Mallick et al. 2000	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Todd et al. 2002		
Bettongia gaimardi	NT	19	272	All year round	106.5	1	3	141.6	0.6	0.6	0.6
		Jones et al. 2009	Jones et al. 2009	Jackson 2007	Jones et al. 2009	Jones et al. 2009	Rose 1987	Jones et al. 2009	Wayne et al. 2016		
Dasyurus viverrinus	NT	19	355	May	365	4.7	1	81.6	0.6**	0.6	0.4
		Jones et al. 2009	Myers et al. 2016	Jackson 2007	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Glen and Dickman 2013		
Dasyurus maculatus	NT	0.3	720	June	365	4.47	1	60	0.6	0.6	0.4
		Glen 2008	van Dyck & Strahan 2008	Jackson 2007	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Glen and Dickman 2013		
Macropus eugenii	LC	73.86	319	January-March	365	1.01	1	168	0.65*	0.65	0.74
		Jones et al. 2009	Jones et al. 2009	Tyndale-Biscoe & Renfree 1987	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Chambers & Bencini 2008		
Macropus giganteus	LC	41.95	813	Oct-Jan	362.79	1	1	288	0.27	0.54	0.95
		Jones et al. 2009	Jones et al. 2009	Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Arnold 1991	Coulson et al 2004	Arnold 1991
Macropus rufus	LC	3.14	547.5	All year	238.5	1	1.5	360	0.27	0.54	0.95
		Jones et al. 2009	Jones et al. 2009	Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Myers et al. 2016	Jones et al. 2009	Coulson et al 2014		
Perameles nasuta	LC	89.99	121.66	All year	53	2.43	2	24	0.53	0.74	0.76
		Jones et al. 2009	Jones et al. 2009	Scott et al 1999 Jackson 2007	Jones et al. 2009	Jones et al. 2009	Jackson 2007	Jackson 2007	Todd et al. 2002		
Pseudocheirus peregrinus	LC	654.82	365	May-Jan	251.6	1.89	1.5	96	0.357	0.357	0.501
		Jones et al. 2009	Jones et al. 2009	Munks 1995/ Myers et al. 2016	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Jones et al. 2009	Pahl 1987		

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Appendix S1

Roadkill data.csv

At 10.6084/m9.figshare.12993470

List of species with roadkill and references: Region/Continent, Order, Family, Species (scientific name), IUCN (conservation status: NE – Not Evaluated, DD – Data Deficient, LC – Least Concern, NT – Near Threatened, VU – Vulnerable, EN – Endangered, CR – Critically Endangered), No roadkill (number of individuals roadkilled, No surveys (number of surveys), No kms (number of kms surveyed), survey period (days), roadkill rate_survey (ind./km/days of survey*365), roadkill rate_survey period (ind./km/ number of days of the survey period*365), Country, Reference, Select (1 – selected species and records for the age-structured models).

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