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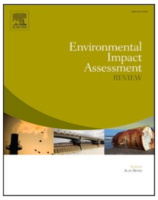

Population abundance should be an Essential Biodiversity Variable in infrastructure impact assessment

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ABSTRACT

Roads, railways, power lines, and other linear infrastructure benefit the growing economy but also impact biodiversity. Environmental Impact Assessments (EIAs) are a key process that should guarantee that biodiversity loss is avoided or mitigated on linear infrastructure projects. Long-term population persistence can be compromised near infrastructure if their impacts are reducing population abundance. This is why the mere presence of an animal population near an infrastructure is not enough to infer that this infrastructure is or is not having an impact and there is a need to monitor population abundance trends. However, population-oriented approaches are rare in studies focused on the impacts of linear infrastructure. We suggest that the best way to evaluate genuine impacts is to include wildlife population abundance among the metrics to be measured in EIAs and monitored in follow-up studies. Population abundance and its trend are good proxies to evaluate the impact of linear infrastructure on the health of local populations and their persistence probability.

1. Introduction

About 3–5 million km of new roads are expected to be built by 2050 globally, with massive increases of road networks in biodiversity-rich regions like several African, Asian, or Oceanian countries (Meijer et al., 2018; see Fig. 1). The global rail network will expand from the current 1.6 to 2.1 Mio km by 2050, a 26 % increase (*IEA,* 2019). By that year, the number of passenger-kilometers and ton-kilometers will more than double current values (*IEA,* 2019). The largest expansion will be, however, in the global high-speed rail network, which may triple by 2050 relative to 2017 levels, mostly in China and Europe (*IEA,* 2019). Similarly, while the commitment to decarbonize energy production supports the growth of renewable alternatives, this will entail an additional 2 Mio km of transmission lines and 14 Mio km of distribution lines by 2030, mainly in India, Southeast Asia, Africa, and China (IEA, 2020). Likewise, some developing countries will see their pipeline networks grow quickly in the next few years, most notably India (by 80 %) and China (by 60 %) (IGU, 2020). Much of the planned linear infrastructure will be developed under the Belt and Road Initiative, mainly across Eurasia and Africa (Ascensão et al., 2018).

However, these different types of linear infrastructure will likely cause many impacts on wild fauna, including habitat loss, barriers to wildlife movement, and direct mortality due to collisions with vehicles and cables (van der Ree et al., 2015; Borda-de-Água et al., 2017; D'Amico et al., 2018). Moreover, linear infrastructure encourages human development in the surroundings, which increases disturbance to animals (Richardson et al., 2017; Kohl et al., 2019), opening remote areas to human access (van der Ree et al., 2015; Borda-de-Água et al., 2017; Richardson et al., 2017).

This massive expansion of linear infrastructure demands careful evaluation of its effects on wild fauna, to provide sound information for mitigating known impacts and more sustainable planning for the future. A research agenda for road – the most studied linear infrastructure – impacts has been suggested to unravel in what circumstances roads

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affect population persistence. This includes studying the relative importance of road effects vs. other effects, the relative importance of the different mechanisms underlying these effects, and under what circumstances can road effects on populations be mitigated (Roedenbeck et al., 2007). However, almost two decades later, we still lack robust answers to these questions. Although some calls have been made to improve assessments and monitoring of road effects and mitigation on wildlife (van der Grift et al., 2013; Rytwinski et al., 2015, 2016; Soanes et al., 2024), both peer-reviewed studies and Environmental Impact Assessments (EIAs) lack proper consideration of the effects of linear infrastructure at the population level (van der Ree et al., 2011; Karlson et al., 2014; Barrientos et al., 2021). We claim that to effectively mitigate the impacts of roads and other linear infrastructure on biodiversity we must understand their effects on wildlife population abundance.

2. Why target wildlife abundance when evaluating the impacts of linear infrastructure?

Linear infrastructure can affect biodiversity at different levels, from individual to population or multi-species levels. Yet, many studies on infrastructure-related impacts focus solely on the number of animals involved, for example, by recording the number of fatalities along a power line or on a road section or monitoring the use of crossing structures. To render these numbers meaningful, we need to convert them to metrics such as per capita mortality or the proportion of individuals crossing, and these metrics require estimates of the population size near the infrastructure (Teixeira et al., 2017; Schmidt et al., 2021). However, this is not currently the case with EIAs or follow-up studies due to several reasons like the lack of retroactive evaluation in many public works or management interventions, the fact that information about the outcomes (if any) falls into the grey literature or that most of actions are tailor-designed and short-term (Lesbarrères and Fahrig, 2012). Ignoring population-level impacts is limiting our ability to evaluate and, consequently, to minimize the threats posed by linear infrastructure development in the conservation of global biodiversity.

Population abundance (and distribution) is the variable directly related to the risk of population extinction (Mace et al., 2008). Furthermore, moving to population abundance studies would allow researchers and stakeholders working on EIA to join the current prevailing trend in Conservation Biology (Callaghan et al., 2024). Abundance is the variable that best characterizes a population, even to assess its short-term responses like those related to, for example, before vs. after infrastructure construction (Pereira et al., 2013). When based on repeat surveys in time series with a standard protocol, relative abundance can be used to estimate the percentage of population change (i.e., the impact of the infrastructure) (Callaghan et al., 2024). Not surprisingly, population abundance is considered one of the few Essential Biodiversity Variables (EBVs), a set of metrics that help prioritize conservation efforts by defining a minimum set of essential measurements to capture major dimensions of biodiversity change (Pereira et al., 2013), that we need to manage to ‘bend the curve’ of biodiversity loss (Williams et al., 2021; Geldmann et al., 2023). Having sound estimates of population abundance or relative population abundance is also relevant to achieving Convention on Biological Diversity targets, like those related to halting species extinction, increasing abundance, protecting genetic diversity, and managing human-wildlife conflicts, or integrating biodiversity in decision-making at every level (Convention on Biological Diversity (CBD), 2022).

Several studies have found that many taxa have lower population abundance close to roads (reviewed in Fahrig and Rytwinski, 2009; de Jonge et al., 2022), and found that the impacts of linear infrastructure are taxon/trait-related (e.g., whereas medium- to large-sized non-carnivorous mammals are less abundant in the proximity of infrastructure, carnivorous mammals are generally more abundant. Also, amphibians and reptiles tend to show negative effects, but their effect zones are smaller than those in endotherms and can be buffered in denser habitats; Fahrig and Rytwinski, 2009; de Jonge et al., 2022). However, we are still far from understanding how the impacts of linear infrastructure threaten local population abundance and, ultimately, persistence as studies on demographic effects of road mortality are still few even for most studied groups (Moore et al., 2023). A recent review found that only 3 to 12 % of scientific papers on road impacts (mortality or habitat loss and fragmentation) or mitigation actions focused on how they were related to local population persistence (Barrientos et al., 2021). The situation is similar for EIAs and follow-up studies, as quantitative analyses related to impact prediction and monitoring are usually lacking (see Karlson et al., 2014; Freitas et al., 2017 for roads).

Ideally, EIAs should include estimates of the probability of population persistence in the infrastructure surroundings over a long period (Fig. 2), at least for a few target species. However, the uncertainty around such predictions is notoriously high, with persistence probabilities ranging, for instance, between 59 and 77 % or 53 and 100 %, depending on the input parameters (Crawford et al., 2018; Desbiez et al., 2020). A more feasible alternative is to predict the change in population abundance (i.e., population trend; Fig. 2) following the construction of infrastructure or mitigation measures. Population abundance and its trend are good proxies for the probability of population persistence because, if an infrastructure reduces population abundance, population persistence can be compromised (Fahrig et al., 1995; Crawford et al., 2018; Desbiez et al., 2020).

Reduction in abundance close to infrastructure can be caused by avoidance of infrastructure (e.g., if traffic interferes with sound

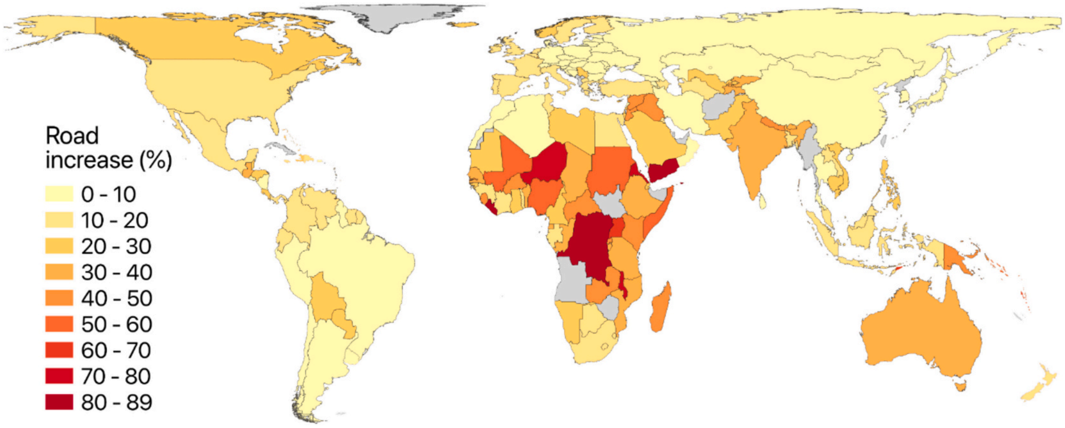

Fig. 1. Development of future global road network. The image shows the expected increase in roads by country measured as the proportional increase by 2050 relative to 2015 (Meijer et al., 2018). Development of the global railway (*IEA*, 2019) and electricity (IEA, 2020) networks are expected to follow similar patterns.

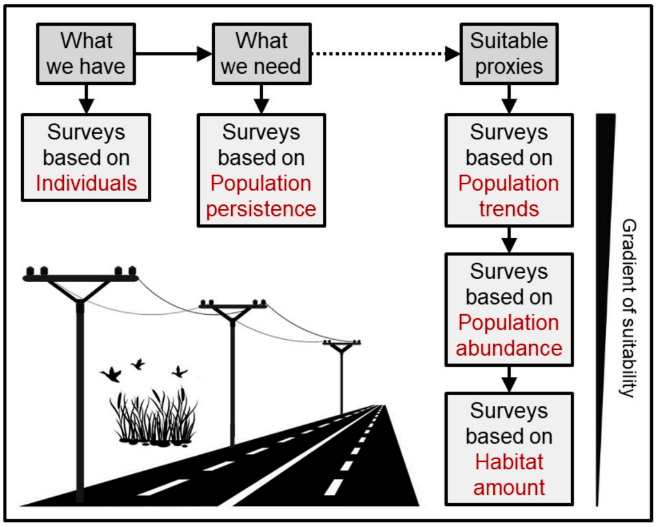

Fig. 2. Conceptual framework for evaluating the ecological impact of linear infrastructure. Current surveys are based on individuals (on the left), but for suitable evaluation we need surveys based on population persistence (in the middle). Population trends (i.e., changes in population abundance between consecutive estimates), population abundance (i.e., number of individuals in the infrastructure effect zone or, at least, in representative subsampling areas), and habitat amount (in the same infrastructure effect zone) are suitable proxies of population persistence (in order of suitability, on the right).

communication, songbirds may refuse to settle near the road; see Ware et al., 2015), due to mortality caused by infrastructure (Fahrig and Rytwinski, 2009), or due to the barrier effect caused by a reduced access to important resources on the other side of the infrastructure corridor that fragments the previously continuous habitat (Riley et al., 2006). Identifying the exact causes of population reduction is challenging but studies that collect before-after data and include comparisons with control sites (i.e., Before-After-Control-Impact designs) to have benchmarks for the variables measured (Roedenbeck et al., 2007; Lesbarrères and Fahrig, 2012; van der Grift et al., 2013; Soanes et al., 2024) improve their inferential strength, although these designs are still rare. Furthermore, a growing claim in this and other fields of Conservation Biology is the need for counterfactuals (i.e., hypothetical scenarios in the absence of human intervention to compare with) for the correct evaluation of both the impacts and the conservation actions implemented (Bull et al., 2021; Coetzee and Gaston, 2021; Grace et al., 2021). Impact assessment can be achieved by defining counterfactual conditions addressed through assumption-based scenario modeling (Katzner et al., 2022). Monitoring population density can help to detect that something is going wrong if the trend is negative. Indeed, a lower density of potential mates will reduce the reproductive potential of the population close to the infrastructure that can cause inbreeding depression and associated loss of fitness, thereby reducing population sizes and genetic diversity (see Hohenlohe et al., 2021 for genetic effects). This, generation after generation, will fuel a spiral of declining density, increasing the probability of reaching extinction in populations living close to infrastructure. Not only population abundance, but also genetic diversity is a variable closely related to population persistence probability in the long run (e.g., 50–100 years). Mortality caused by linear infrastructure or reduction of dispersal rates leading to population subdivision into smaller units could increase inbreeding rates by reducing gene flow, resulting in inbreeding depression and population fitness reduction, ending in a population decline (Hohenlohe et al., 2021); and genetic units with smaller effective population sizes (i.e., the number of individuals that effectively participates in producing the next generation) are more likely to go extinct (Sunnucks and Balkenhol, 2015; Hohenlohe et al., 2021; Frère et al., 2023). Nevertheless, landscape genetic approaches in infrastructure impact assessment are still underutilized, partially due to insufficient communication between researchers and stakeholders (Sunnucks and Balkenhol, 2015). In interpreting such changes in population abundance (or genetic diversity), it is important not to underestimate the significance of comparatively small changes through time. For example, we might predict or observe a very small, apparently "insignificant" decline in a given species' population size over the short term following infrastructure construction. However, if the impact is sustained over time, this small but continuous decline might portend the ultimate extinction of the population. Moreover, populations might present delayed and/or progressive responses, thus not being detected when monitoring focuses only on sudden and constant effects (Thiault et al., 2017). Including population abundance in follow-up studies would help to solve this problem.

Most EIAs focus on intermediate measures such as casualty counts on a stretch of power line or road, or animal crossings over a wildlife passage as estimators of impact or mitigation effectiveness. Locations with high concentrations of casualties (mortality hotspots) are often used to identify locations where mitigation is needed, and their lack as a sign that the infrastructure has no impact. However, not considering the population abundance can lead to misinterpretations. Low mortality rates can be due to low population abundance caused by past mortality or animal avoidance of the infrastructure (Teixeira et al., 2017; Ascensão et al., 2019a). Similarly, misinterpretations can arise when crossing rates over a wildlife passage are used to evaluate mitigation effectiveness, as they can be misleading if there are no estimates of population abundance (i.e., benchmark to compare with; Soanes et al., 2024). For example, crossing rates may be high relative to other locations on the road simply because the initial population abundance was higher near the wildlife passage. Also, it can be incorrect to assume that mitigation has failed because crossing events are few if, for example, the regional distribution of the population has changed while the infrastructure was being built (Schmidt et al., 2021). At this point, it should be noted that the conservation status of the species (closely related to their life history traits) must be considered, since threatened species tend to have low densities and any loss becomes dramatic.

3. Predicting the effect of a planned infrastructure or mitigation on population abundance is challenging

We need robust surveys designs (i.e., the combination of good sampling strategies with suitable field methods intended to increase the representativeness of data or reduce biases) for measuring the abundance of focal species close to the infrastructure with surveys based on population abundance, as a proxy for population persistence (Fig. 2). Some well-designed examples are the use of camera-trapping before and after the construction of crossing structures (e.g., Schmidt et al., 2021), or radio-telemetry data that provide detailed information, not only on individual crossings but also on the full territory use by animals relative to the infrastructure location (e.g., Riley et al., 2006). However, robust survey designs do not necessarily include high-tech methods, as they can also be based on simpler, but standardized, counts of species abundance or relative abundance with randomized, stratified sampling fieldwork protocols. Once we have this high-quality data, we can evaluate how population persistence will be threatened by infrastructure (Fig. 2), thus anticipating necessary conservation and mitigation actions. Time-series data on population abundance are critical for the assessment of the impact of interventions on populations, and the use of robust analyses to identify changes in population trends should be encouraged (Wauchope et al., 2021).

However, predicting the effects of infrastructure or mitigation actions on animal populations can require specific information on their effects on the different subsets of the population. For instance, Row et al. (2007) found that all the reproductive classes of black ratsnakes (*Pantherophis obsoletus*) examined (male, non-reproductive female, reproductive female) crossed the road, a risky behavior for this species since 3

% of the crossings resulted in roadkills. This result translated into a reduction of the population viability in the long term by 92 % (Row et al., 2007). Using a similar modeling approach, Murphy et al. (2022) estimated that reduced predation on roadside nests can compensate for about 3 to 6 % of annual roadkill on adult painted turtle (*Chrysemys picta*) populations. In many situations, adult survival (especially female survival) is key for population abundance and ultimately population persistence (Crawford et al., 2018; Desbiez et al., 2020). Information about the age and sex bias of infrastructure impacts can therefore be important for accurately estimating population-level effects (Moore et al., 2023) but, currently, most EIAs are limited to recording the location and number of roadkills for most species and contexts.

We acknowledge that detailed population-level data on mortality, reproduction, or dispersal rates needed for sound estimates of population impacts are time- and budget-consuming. However, the amount of habitat can be an acceptable proxy for abundance when species abundance for different habitat types is known (e.g., Turlure et al., 2010; Bean et al., 2014; see Fig. 2), as species usually reach higher abundances in preferred habitats. Near the infrastructure, the population can be depressed relative to the capacity of the habitat because of infrastructure-related avoidance or mortality (Fahrig et al., 1995; Teixeira et al., 2017; Ascensão et al., 2019b). In that case, habitat amount is an indicator of potential population abundance as opposed to actual population abundance (D'Amico et al., 2016), and as such can indicate where mitigation would be effective in restoring populations to their potential abundance.

4. Including population-level monitoring in EIAs

It is increasingly recognized that sustainable linear infrastructure will require consideration of population impacts and their potential mitigation in the very earliest stages of project planning (Lesbarrères and Fahrig, 2012; Ascensão et al., 2018). Strategic Environmental Assessments (SEAs) need to mainstream the goal of estimating population-level responses in impact assessments. SEAs are especially suitable for evaluating the cumulative effects of different types of linear infrastructure as it is a systematic process for evaluating the environmental implications of proposed development policies, plans, or programs, instead of disconnected individual projects. SEAs could indicate the selection of target species and use existing data to model population trends due to the cumulative effects of different types of infrastructure or at the scale of the entire network. Then, EIAs and follow-up monitoring at the project level could collect missing population data for target species to parametrize and validate population models. This would allow one to make predictions of population trends over time in response to the project or to planned mitigation, as part of the assessment of the project.

As commented above, a focus on long-term population persistence would be ideal but, in general, it will be more feasible to assess changes to population abundance (Fig. 2). Ideally, studies should go beyond measuring average changes in population abundance and should focus on analyzing changes in population trends due to the presence of the infrastructure or a mitigation intervention, at least for target species (Wauchope et al., 2021). Projected negative trends would indicate that the planned infrastructure is not sustainable and should therefore be mitigated by considering the mitigation hierarchy (CCBI, 2015).

CRediT authorship contribution statement

R. Barrientos: Conceptualization, Writing – original draft. **F. Ascensão:** Conceptualization, Writing – review & editing, Visualization. **L. Fahrig:** Conceptualization, Writing – review & editing. **F.Z. Teixeira:** Conceptualization, Writing – review & editing. **M. D'Amico:** Conceptualization, Writing – review & editing, Visualization.

Declaration of competing interest

The authors declare no conflict of interest in the manuscript entitled Population abundance should be an Essential Biodiversity Variable in infrastructure impact assessment.

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Data availability

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

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