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LETTER

Mainstreaming ecological connectivity in road environmental impact assessments: a long way to go

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ABSTRACT
Road networks affect ecological connectivity, which has implications across different levels of biological organization. There are compelling reasons and sufficient approaches and tools to mainstream ecological connectivity into environmental impact assessments (EIAs) of road projects. In this letter, we discuss ways of overcoming the existing gaps and obstacles in the consideration of connectivity loss in EIAs and how to improve mitigation. The selection of target species, shifting from single to multispecies approaches, and the evaluation of scale optimization are challenges that need to be overcome. We also discuss that the mitigation hierarchy, no net loss targets, and the principles of adaptive management should be applied to increase the effectiveness of mitigation measures. We propose to increase the cooperation between stakeholders and practitioners to enhance co-production and build capacity to conduct evidence-based EIAs for assessing ecological connectivity. Finally, we identify directions for future research that can contribute to integrating connectivity into EIA practice.

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Roads are an important source of disturbance in ecological systems and are distributed in a large network worldwide. One of the major effects of road networks is connectivity change, which has implications across levels of biological organization, from individuals to entire ecosystems. Roads can pose barriers to the movements of individuals and genes within and between populations, decreasing their access to resources and their fitness (Van Der Ree et al. 2015). These can affect population abundance and persistence, which can ripple through ecological communities, altering patterns of species composition, richness and the interactions among them, and ultimately affecting ecosystem function (Mestre et al. in press; Barrientos et al. 2021). Furthermore, roads could act as corridors, for example, by facilitating the colonization of invasive species (Bergamin et al., 2022; Brown et al. 2006), also affecting biological organization levels and processes, but sometimes with an opposite direction. For simplification, hereafter we will focus on connectivity loss, but our concerns and suggestions could also be applied to the context of connectivity increase.

There are compelling reasons and sufficient approaches and tools to mainstream the evaluation of connectivity loss into environmental impact assessments (EIAs hereafter) of road projects. Our aim in this letter is to highlight the poor consideration of ecological connectivity loss in EIAs of road projects and discuss ways of overcoming the existing gaps and obstacles to their proper consideration, including adequate actions to mitigate connectivity loss. We also identify some directions for future research that can contribute to integrating connectivity into EIA practice. Although our concerns stem from our experience in Brazil, we think our recommendations can encourage a broader audience, not only from Southern-hemisphere countries which are experiencing a strong and fast expansion of their road networks but also from countries that are reviewing their licensing practices or are financing the expansion of road networks. Moreover, our recommendations are useful both to EIA practitioners and road ecology researchers investigating the effects of roads on ecological connectivity.

Populations of many species occur in landscapes with disjunct habitat patches and their persistence may also depend on individual movement between patches, but some features of these landscapes – such as transportation infrastructure – can hinder such movements (Fahrig et al. 2021). Currently, there is a wide range of definitions for the concept of connectivity that are applied depending on the aims and metrics used, from the degree to which a landscape facilitates movement, to the functional relationship among the spatial distribution of habitat patches to the ease of

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movement within a landscape (Kindlmann and Burel 2008). Irrespective of the definition used, movement success is central to the concept of connectivity (Fahrig et al. 2021). Here, we are considering a broad concept of connectivity that includes structural and functional connectivity (Kindlmann and Burel 2008).

Landscape-scale effects are regularly neglected in EIAs of road projects (Karlson et al. 2014; Jaeger 2015; Freitas et al. 2017). Good practice guidelines from regions like Europe recommend considering connectivity in EIA (Iuell et al. 2003) and the need to maintain ecological corridors is usually mentioned. However, connectivity loss, specifically, is only superficially assessed in EIA (Karlson et al. 2014; Freitas et al. 2017; Karlsson and Bodin 2022), and environmental impact statements usually lack proper quantitative assessments and predictions of connectivity loss (Patterson et al. submitted(a); Jaeger and Torres 2021). These shortcomings originate even before the elaboration of environmental impact statements since the scoping practice concentrates on requiring descriptions of baseline conditions instead of focusing on impact prediction and assessment (Borioni et al. 2017) and the estimation of effect sizes. Moreover, in some countries, there are no explicit policy requirements and laws to include connectivity in the EIA process (Patterson et al. submitted(b)), failing in the implementation of connectivity conservation plans (Keeley et al. 2019).

Tools to measure connectivity loss and evidence-based solutions to mitigate it are widespread in the literature. Different types and levels of data can be used for connectivity modelling, representing different ways of how species use and move through the landscape: from landcover or habitat suitability maps, resistance maps, to source-target patches or network nodes with movement rules for individuals. This information can come from empirical movement data, potential species occurrence maps, or even expert opinion (Correa Ayram et al. 2016). Least-cost path, circuit theory, graph theory, and individual-based models are just a few examples of the vast amount of approaches and tools available (see details in Hilty et al. (2020) and more examples in the Connectivity Toolbox at the Conservation Corridor website (CCSG 2022)). Some approaches have been proposed or applied specifically within the context of road routing, such as graph theory, which has been used to identify important connections among patches to be avoided by road construction (Vasas et al. 2009), for proposing priority segments for defragmentation of road networks (Gurrutxaga and Saura 2014; Loro et al. 2015; Ascensão et al. 2019), or to restore connectivity by indicating locations for mitigation measures on roads and railways (Clauzel 2017; Tarabon et al. 2022). However, these approaches have seldom been applied to EIAs worldwide (Patterson et al. submitted(b)).

One step in implementing connectivity analyses in EIA is the selection of target species or groups as surrogates for assessing this impact and supporting decision-making (Teixeira et al. 2020a). These species or groups of species can be studied in more detail and then used as indicators to infer how the loss of ecological connectivity caused by road projects will affect other species or biodiversity values. However, to apply the use of surrogate species or groups, it is important to test their efficiency in representing connectivity patterns for other taxa (Brennan et al. 2020). We also echo the recommendation to move connectivity analyses from single species towards a multispecies approach, as single-species models might ignore the connectivity needs of co-occurring species (Brodie et al. 2015; Brennan et al. 2020; de Rivera et al. 2022; Tarabon et al. 2022). Previous research suggests that multispecies connectivity models should be tailored to ecologically similar and disturbance-sensitive species to optimize their effectiveness (Brodie et al. 2015). Multispecies connectivity is important to safeguard complex species interaction networks and ecosystem functioning and biodiversity maintenance. Connectivity loss can have cascading effects on ecosystem functioning and biodiversity due to the disruption and/or reorganization of species interactions that regulate ecosystem services on which we depend upon (Mestre et al. in press). Shifting from single-species to multispecies approaches will pose important challenges for practitioners. There is a demand for the development of analytical methodologies, capable of considering concomitantly the connectivity needs of multiple species of concern.

The choice of spatial extent to perform ecological connectivity modelling is another challenge, and optimizing the scale is a major advance needed (Cumming and Tavares 2022). The current practice is the definition of arbitrary limits for the study area in which connectivity will be assessed during EIA, without the appraisal of the scales at which ecological processes of interest are expected to be stronger (Patterson et al. submitted; Karlson et al. 2014). Scale should be determined based on target groups and the relevance of impacts of the road project. Ecological processes related to connectivity could operate on daily movements at a local scale (Clauzel et al. 2015) or on migratory movements that occur at a regional or global scale (Fullman et al. 2021). At local and regional scales, there is evidence for road effect zones from 1 to 5 km wide in which reduced population abundance was observed for hundreds of species of birds and mammals, respectively (Benítez-López et al. 2010). However, these scales might not be adequate for the assessment of the loss of ecological connectivity by road projects, as movement success might be affected at larger scales by the implementation of linear infrastructure (see example for modelling migratory connectivity (Fullman et al. 2021). From the above examples, it is clear that multi-scale analyses, the evaluation of scale optimization (Ashrafzadeh et al. 2020; Alvarenga et al. 2021), and the definition of EIA study areas embracing the underlying ecological processes of interest should be research priorities.

Connectivity tools are frequently used to find locations for roadkill mitigation; however, contrary to the naive and widespread expectation, sites with higher mortality are not always located in sites with higher landscape connectivity (Cerqueira et al. 2021). These two effects (reduced connectivity and increased mortality) should be measured in distinct or associated ways (Boyle et al. 2017; Sevigny et al. 2021). Road segments with both high expected crossings and high mortality risk should be the highest priority for mitigating both effects combined, while locations identified only as important crossing spots could be used to inform mitigation of connectivity loss and areas with a high number of fatalities should be used to mitigate road mortality. Not only EIAs but the ecology literature also confounds multiple mechanisms linked to a single road effect, and the proper recognition of the mechanisms behind the effect of interest is essential to recommend appropriate mitigation measures (Teixeira et al. 2020b).

To mitigate connectivity loss, it is also important to act on planning stages prior to the project-based environmental assessment. Strategic Environmental Assessments (SEA) could be the framework for this task with analyses of ecological connectivity at multiple scales and in multiple tiers (Cumming and Tavares 2022). As even a small and localized project can disrupt regional connectivity, the EIA process should consider the additive and synergic impacts from multiple activities and stressors through a cumulative effect assessment (Harker et al., 2021). If well conducted, SEA could rise recommendations at a regional and strategic level, allowing the minimization of impacts of development projects on biodiversity (Whitehead et al. 2017).

Mitigation planning in EIA should explicitly recognize and follow the mitigation hierarchy (Milner-Gulland et al. 2021). The mitigation hierarchy framework was designed to limit the negative impacts of development projects on biodiversity and ecosystem services by iteratively addressing four key actions: 'avoid', 'minimize', 'restore' and 'offset'. Although multilateral environmental agreements recognize the need to maintain and restore habitat connectivity, the spatial configuration is hardly considered in the mitigation hierarchy (Bergès et al. 2020; Tarabon et al. 2020). To reduce connectivity loss, each stage of road building and operation may be subject to interventions applying the mitigation hierarchy framework. Locations of high landscape connectivity should be avoided during road routing, and then long-span bridges and crossing structures should be designed for specific targets, combined with other adaptations of the road project to minimize connectivity loss. Residual connectivity loss detected during road operation should be restored by road retrofitting, for example, by improving existing wildlife crossings and installing new ones aiming to restore movement back to pre-road levels. Only after alternatives for these three first steps have been exhausted, residual losses should be compensated by enhancements in ecological connectivity off-site, and only as a last resource with financial compensation (Villarroya et al., 2014).

No net loss is an increasingly influential target in impact assessment, which means that residual losses should be counterbalanced (Maron et al. 2018). In impact-specific no-net loss, counterfactual scenarios describing what would happen to the target outcome without the impact and the mitigation/offset need to be defined (Maron et al. 2018). In the case of the loss of ecological connectivity, it is key to determine what reference comparison for structural or functional connectivity is being considered, and what type of ecological outcome should be monitored, such as individual or genetic cross-road movements (Maron et al. 2018). An important policy gap is the definition of what should be targeted and acceptable in no net policies, for example, if the same amount of movement should be a target or if an outcome of maintaining population abundance and persistence probability can be reached with lower movement rates than on a pre-road condition. Future research should address and compare scenarios with different expected outcomes and assess the consequences of different connectivity scenarios, arriving from differing planning frameworks and including feasibility within a road network implementation context (Augustynczik, 2021).

An important step in implementing connectivity analyses in EIA is testing and validating connectivity models to ensure evidence-based mitigation. Model validation is an important step to guarantee the use of the best decision-making tool and models that are not validated and can result in inaccurate management decisions (Laliberté and St-Laurent 2020). Post-construction monitoring is paramount to assess mitigation effectiveness and inform maintenance and adjustments needed in mitigation based on the principles of adaptive management (van der Grift et al. 2015) within the current project and also for future ones. Validating models of connectivity loss due to roads and the effectiveness of mitigation would require collecting data of cross-road movement before and after road construction and in sites with and without the presence of mitigation measures. Crossings could be inferred from different types of data sources, from individual telemetry, mark-recapture or genetic to cameras or track beds (e.g. Zeller et al. 2020). A part of the data could be used to train/fit the model and another part to evaluate its performance in predicting connectivity. Finally, study designs and models should also consider that landscapes are dynamic and movement and connectivity patterns are not constant over time (Simpkins and Perry 2017; Jennings et al. 2020).

In order to mainstream connectivity analyses and mitigation in EIA, we need to intensify the cooperation between researchers, EIA practitioners, road constructors, regulators, and other stakeholders to enhance co-production and support and build capacity to conduct evidence-based project EIAs (Beier et al., 2017; Sahraoui et al. 2021). Cooperation is essential to accelerate the implementation and adaptation of connectivity analyses to the complex process of EIAs at the project level. Improving the scoping process might be our best opportunity to do that, considering the different phases of the EIA process (screening, scoping, studying, evaluating, deciding, monitoring and the many steps within and between project learning feedbacks). Furthermore, connectivity loss can also be mainstreamed in EIA by improved requirements and enforcement from different state and private agencies financing road building and network expansion.

Although connectivity research has advanced tremendously in the last decades, there are still major improvements needed in relation to the proper consideration of the loss of ecological connectivity in EIA. We highlight here some of the reasons why this impact should be integrated in EIA of road projects since roads can pose a barrier or filter to the movements of animals which have implications across levels of biological organization. We discuss some issues and approaches that need to be considered when mainstreaming connectivity into EIAs, such as a better choice of the spatial extent to be studied, the selection of target species or groups, the inclusion of model validation, the adoption of the mitigation hierarchy and of the principles of adaptive management. We hope that this letter can contribute to the discussion on how connectivity loss can be better assessed and mitigated within the road infrastructure context.

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