Measures to reduce population fragmentation by roads: what has worked and how do we know?

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Roads impede animal movement, which decreases habitat accessibility and reduces gene flow. Ecopassages have been built to mitigate this but there is little research with which to evaluate their effectiveness, owing to the difficulty in accessing results of existing research; the lack of scientific rigor in these studies; and the low priority of connectivity planning in road projects. In this article, we suggest that the imperative for improving studies of ecopassage effectiveness is that road ecology research should be included from the earliest stages of road projects onwards. This would enable before–after–control–impact (BACI) design research, producing useful information for the particular road project as well as rigorous results for use in future road mitigation. Well-designed studies on ecopassage effectiveness could help improve landscape connectivity even with the increasing number and use by traffic of roads.

Ecopassages: a solution to reconcile roads and wildlife

Roads and traffic have large effects on a wide range of animal species [1], and these effects can be similar in magnitude to other impacts, such as habitat loss [2]. Roads affect wildlife through several mechanisms [3]: populations are reduced through direct mortality owing to collisions with vehicles; traffic disturbance (e.g. noise, lights and motion) reduces the quality of habitat near roads (e.g. [4]); and, for many species, roads are barriers to movement owing to physical obstacles, such as fences, or to a behavioral unwillingness of the animal to move onto the road surface [5,6]. The impact of roads on the movement of animals represents a decrease in landscape connectivity [7], and can lead to decreased habitat accessibility [8] and reduced gene flow [9,10].

Solutions for mitigating the effects of roads on wildlife mainly focus on the installation of wildlife crossing structures ('ecopassages') to improve connectivity [11]. Many types of ecopassage have been proposed and built, but there is little research on which to base an informed evaluation of their effectiveness [12–15]. van der Ree et al. [11] reviewed 123 studies of ecopassage effectiveness and concluded that they contain little useful information for evaluating whether the ecopassages have mitigated the

effects of the road(s) on connectivity. Most studies simply record the presence of animals in or moving through ecopassages, with no information on pre-ecopassage movement rates or on movement rates at control (non-ecopassage) sites. Without such comparisons, evaluation of the mitigation effectiveness of the ecopassage is not possible. Here, we suggest possible reasons for the scarcity of useful information on the effectiveness of ecopassages. We also briefly summarize the evidence that does exist and suggest potential solutions to improve knowledge in this area.

Possible reasons for the lack of evidence concerning the effectiveness of ecopassages on the restoration of landscape connectivity

Difficulty of accessing research results

A review by Pullin et al. [16] showed that most conservation actions remain experience based and rely heavily on traditional land management practices and conjecture. In fact, many management interventions remain unevaluated. Most road planning is under government ministries or departments where information, although public, is usually contained in internal reports ('grey literature') that are not broadly distributed. Some of this work has been reported in conference proceedings available on the internet [e.g. International Conference on Ecology and Transportation (ICOET), formerly ICOWET ('W' for Wildlife)], but most has not been published in the primary literature. Therefore, in an era when most scientific results are widely available through the publication process, road mitigation research remains somewhat in the dark ages.

There are two main reasons why most research evaluating ecopassages has not been reported in the scientific literature. First, the research is mostly conducted in a specific applied setting in which information is desired for a particular wildlife crossing project. The government agencies conducting the work often do not have any interest, incentive or requirement to publish the work more broadly. Second, as discussed in the next section, these studies are frequently characterized by a lack of scientific rigor [11].

Case-by-case post-construction studies: lack of scientific rigor

Studies of ecopassage effectiveness are frequently designed without consideration of other similar studies (partly owing

to the inaccessibility of the literature; see above). Approximately 15% of the studies involve a single ecopassage [11] and, in these cases, the study design is unreplicated. This leads to the difficult situation where results are unique to a specific location and cannot easily be compared, in turn causing transportation agencies to expend considerable resources repeating the research or installing ecopassages that had not really been shown to be effective [17].

An important reason for the low quality of research on ecopassage effectiveness is that such research projects are not initiated or even planned until after the ecopassage is in place. Typically, after the passage is built, the transportation agency that built it issues a 'call for proposals' for research to evaluate its effectiveness. Road ecologists can submit proposals directly to the agency, or a consulting company might submit a proposal that includes road ecologists as expert advisors. In either case, the research is likely to produce equivocal or weak results because of a lack of benchmark or baseline data from before the ecopassage (and the road itself) was in place.

By contrast, if road ecologists and their research needs were included throughout the road design and construction process, road ecology studies could be designed with much higher inferential strength, as advocated by Roedenbeck *et al.* [18] and van der Ree *et al.* [19]. This would entail replicated designs in which connectivity is evaluated before and after the ecopassages are in place, and compared with control sites in which no ecopassage is installed (i.e. a BACI design). There are to date only a few such experiments [15,20]. Of the 61 empirical studies evaluating ecopassages reported in the ICOET conference proceedings since 1996, 44 (72%) had neither before–after data nor control sites. These studies simply reported evidence for the presence or numbers of animals found in particular ecopassages and thus cannot be used to evaluate their effectiveness to mitigate road effects on animal crossing rates [11,18,21]. Given that ecopassages are becoming a common feature of new road construction, this represents a huge missed opportunity to evaluate and compare their effectiveness rigorously [15]. The few BACI studies that do exist (e.g. [22–27]) illustrate the importance of good study design. For example, although Elliot and Stapp [26] found that wildlife used an underpass, comparison of road kill data from before and after installation of the underpass indicated no change in road kill numbers. The authors concluded that fencing would be needed to make the underpass effective, a conclusion they would not have reached using data on underpass use only [11].

An additional study design problem is that monitoring of ecopassages is usually of short duration; van der Ree *et al.* [11] found that the average monitoring period (given that monitoring was occurring) was 1.7 years post-construction. The length of time needed to detect an effect of an ecopassage on animal movements depends on the expected frequency of movements: the rarer the movements, the more years will be required to develop a good estimate of movement rate. This means that more years will be needed to document movement rates for species with low population densities. In addition, for some species, there is a delay in use of a passage until the animals become aware of its presence [28]. The number of years needed for monitoring will also depend on the measurement end-point; for example, documentation of across-road movement rates requires shorter monitoring periods than does documentation of decreasing genetic isolation [29]. Power analysis should be used to determine the monitoring time needed to detect a change in crossing rates or gene flow, depending on the objective. Currently, the post-construction monitoring period is usually based on funding availability, which is usually less than adequate.

Low priority for connectivity in road planning
An additional reason for the lack of solid information on ecopassage effectiveness is that conducting research on this topic requires close collaboration between ecologists and road planners (Table 1), but road planners often appear unconvinced of the importance or value of such research. Road ecologists who study animal movements would like their research results to influence road design, but for transportation planners, animal movements are a minor concern; their main focus is on how to make safe roads that will allow transportation of people and goods at minimum cost. Adding even a relatively small amount of money to the road construction budget for a rigorous research project on ecopassage effectiveness remains low on the priority list for road planners. This leads to a 'Catch-22' situation, where the absence of such research contributes to a lack of interest on the part of road planners, and that lack of interest hinders research because collaboration with (and funding from) road planners is necessary for such research to take place. The implications of such research for future planning can even present a disincentive for planners to collaborate with researchers [30]. For example, a reasonable inference from a scientific study might be that mitigation is not possible and so a road construction project should not go ahead. This information will usually be poorly received by decision-makers who typically start from the assumption that biological conservation will not actually stop road construction. Furthermore, arguments frequently used by road ecologists (e.g. the precautionary principle) are often considered of secondary importance by planners in the face of compelling economic counterarguments [31].

Sound research on ecopassage effectiveness is also limited by the cost of conducting such research. We note, however, that although these costs are high relative to other types of ecological study, they are typically low in comparison to the budget for the entire road project. As discussed above, such research requires collaboration between road planners and road ecologists. In Table 1, we describe the steps in such a research project. Direct communication between the researcher and the road planners is needed at most steps in this process. For example, the appropriate species and sites to study will depend on what is actually planned for the road alignment and ecopassages, and the funding for species monitoring will depend on incorporation of these costs into the road project budget. However, the political agenda is often too shortsighted and economic resource availability is too unpredictable to allow a full BACI study, resulting in studies with low inferential strength. The uncertainty associated with the results of such studies then reduces the incentive for planners to take

Table 1. Steps for including research on ecopassage effectiveness in a road construction project[a]

Step	Description
1. Preconstruction: determine the potential connectivity impacts of the road in the area of concern	• Identify the set of species whose movements are most likely to be affected by the road, as well as their relevant ecological requirements • Identify the relevant spatial and temporal scales for these species, the former based on movement range and the latter based on movement frequency
2. Identify goals for the ecopassages	• Set quantitative targets for species (e.g. increased frequency of crossing) • Determine type(s), size(s) and other design criteria for the planned ecopassages
3. Identify control and ecopassage sites and collect 'before' data	• Determine the number and location(s) of planned ecopassages as well as two types of 'control' site [(i) no road planned at the sites; or (ii) road but no ecopassage planned] using a suitable (e.g. randomized or blocked) experimental design • Determine alternative designs in case resources are insufficient to implement the optimal design • Conduct power analysis to determine the replication (in time and across sites) needed to detect effects of the ecopassages • Design monitoring protocols for both the future ecopassage sites and the control sites • Collect 'before' data on animal movement at the future ecopassage sites and the control sites
4. Post-construction monitoring	• Install the ecopassages • Continue with the same protocols for monitoring animal movement at the ecopassage sites and the control sites for a period determined by the power analysis (see above) • If possible, maintain the same field personnel throughout the study to reduce the observer bias and limit training needs
5. Analyze data and report	• Analyze data with regard to the goals in Step 2 and draw conclusions. The ecopassage is partially successful in maintaining connectivity if the reduction in road crossings before versus after the road is built is less at the ecopassage sites than at the no-mitigation control sites. The ecopassage is completely successful in maintaining connectivity if the difference in road crossings before versus after mitigation is the same for the ecopassage sites as for the no-road control sites. • Report on the study results to sponsors, stakeholders, other transportation agencies and road ecology researchers. Publish results in peer-reviewed journals that can be accessed by the widest audience • If the mitigation is unsuccessful or less successful than desired, redesign it and repeat the process

[a]Research is needed to evaluate effectiveness of ecopassages. This is best done by incorporating a BACI research design [18] directly into a road project. This should result in both improved ecological condition for the site itself and new information that can be used to improve other road projects either at the same or other sites.

the research results seriously. This, in turn, feeds back to reinforce the lack of funding for high-quality road ecology studies, leading to the current situation in which there are few studies with high inferential strength. The result is that road projects continue to be built with only token attention paid to their effects on wildlife movements, an insidious process referred to as the 'Zerschneidungszirkel' (fragmentation spiral) by Jaeger [32].

What types of ecopassage work?
Various types and sizes of ecopassage have been evaluated in terms of their use by a range of taxa [33–35], including 'green bridges' or wildlife overpasses over the road, and wildlife underpasses extended under the road, which vary from small culverts or tunnels to larger culverts and large open-span bridges. Use rates suggest that different species preferentially use different ecopassage types, and some species require particular features in the passage. This, combined with success stories for individual species (Box 1), creates the expectation that a 'connectivity-friendly' road is one with an array of different types of ecopassage [36]. However, we suggest that this picture has developed mainly because each study has either evaluated only a limited range of passage types, or was focused at the outset

Box 1. Success stories are taxon specific

No discussion about road mitigation measures is complete without reference to the wildlife underpasses and overpasses in Banff National Park, Canada. The effectiveness of these has been reported in the primary literature and the international media [12,36]. Research indicates that carnivores use passages more frequently than do small mammals [45]. In the presence of human activity, carnivores were less likely to use passages than were ungulates, and carnivore use of the passages was correlated with landscape variables, whereas ungulate use was correlated with structural variables of the passage itself [12]. Evaluations of these passages have been useful in designing other large ecopassages; an example is shown in Figure 2 (main text).

Other work also indicates taxon-specific needs for ecopassages. For example, many small animals will not swim through inundated culverts, but will use culverts retrofitted with shelves attached to the inside of the walls along which they can walk [46]. Many amphibians will use only moist structures, so they will not use most overpasses or dry tunnels [47]. Mule deer require underpasses that are at least 6 m wide and 2.5 m high [48].

In fact, the most well-known cases of successful ecopassages are those aimed at mitigating the barrier effect of roads for individual species. For example, when State Road 84 in Florida was converted to Interstate 75, fencing and passages were put in place for the endangered Florida panther (*Puma concolor couguar*). Sixty-five kilometers of the new road were lined with 3.4 m-high fencing topped with barbed wire, and 24 panther underpasses were built at intervals along the road. Panthers use the underpasses regularly, and there have been no panthers killed on the stretches of road protected by the passages and fencing [49]. Another example is the turtle fencing installed at Jackson Lake, Florida, to direct migrating turtles towards a culvert under Highway 27. Before the fencing was installed, 100% of turtles attempting to cross the road were killed; this was reduced to <1% after installation of the fencing [50]. Although taxon specific, these case studies demonstrate connections between road ecologists and transportation planners that have resulted in the implementation of ecopassages that mitigated the road effects on connectivity, and where the research demonstrating this success was rigorous and the results made accessible.

on a particular species. In fact, when all studies on ecopassages are viewed together, the conclusion that a variety of passage types is required is not supported. Rather, two simple patterns become apparent: (i) one passage design that works for most species is the 'extended stream crossing', an elongated, open-span structure over a natural stream, including wide banks on both sides; and (ii) for effective functioning of an ecopassage, fencing is needed to keep animals off the road, to avoid road mortality between ecopassages and to direct animals towards the ecopassages.

Ruediger [37] supports the suggestion to 'replace culverts with bridges or structures that span the stream banks at high flow, plus allow room for wildlife to cross on either side' (i.e. extended stream crossings). We suggest that an extended stream crossing should be approximately five times the width of the stream at high water, thus allowing movement of terrestrial animals on dry banks. The height of the passage over the dry banks should be sufficient to allow passage of the largest terrestrial animal in the area (Figure 1). Although extended stream crossings might be more expensive to install than are culverts [38], in the long-term they should pay off because they provide connectivity for most animals, large and small, terrestrial and aquatic. In addition, as pointed out by van der Ree *et al.* [11], despite their high cost relative to other passage types, the cost of such stream crossings is still low within the context of the entire budget of a road construction project. Overall, extended stream crossings are probably the most cost-effective way of improving connectivity across roads.

In addition to the design of an ecopassage, its location has a large affect on its ability to enhance or maintain connectivity. A typical approach is to use road-kill hotspots as indicators of locations where large numbers of animals attempt to cross roads and so where ecopassages would be appropriate. Several authors have analyzed road-kill distribution data to identify local and landscape-scale factors that predict road-kill hotspots. Not surprisingly, these studies confirm that such hotspots are generally associated with locations where species habitat occurs next to the road or on both sides of the road [39]. However, in comparing locations with similar habitat availability, Fahrig *et al.* [40] found that amphibian road-kill hotspots occurred in sites with lower traffic, suggesting that mortality from road kills had already reduced local populations in habitats near high-traffic roads, resulting in fewer road-killed amphibians. Therefore, although road-kill hotspot analyses can be used as a general indicator of habitat–road kill associations, they should not be used as the sole indicator of the best sites for installing ecopassages. Simulation models that include animal movement behavior and habitat distribution could be used to identify the most likely crossing sites for animals, which would indicate the best placement of ecopassages. Locations where the model indicates high crossing rates but where few road kills are actually observed could indicate locations where the population is depressed owing to past road kill and so where ecopassages might lead to population recovery. As far as we are aware, this type of modeling has not yet been done.

Potential solutions for improving the impact of road mitigation research

The overarching imperative is that road ecologists and road ecology research should be involved throughout the road project, beginning with the earliest stages of planning. Transportation planning occurs over many years, even decades. Involving road ecologists throughout the process will facilitate incorporation of ecopassages into road projects, with the potential to improve connectivity across existing roads and mitigate connectivity loss on new roads. In addition, early involvement of road ecologists would allow them to use the road project itself as a research project (Table 1), providing valuable information for connectivity mitigation on future road projects.

Opportunities for improving connectivity on existing roads and reducing impacts on new ones

Most transportation projects involve improvements and expansions of existing infrastructure to accommodate more traffic, rather than the building of new roads [13,41–43]. These projects represent an untapped opportunity for improvement of connectivity. For example, when a road intersects a small stream, water flow across the road is typically maintained through a drainage culvert underneath it. However, many animals will not use standard culverts. If road ecologists were included in the planning phases of road improvement projects, they might suggest replacing culverts with extended stream crossings (Figure 1) to allow passage of animals. As a second example, many limited-access roads have concrete safety barriers ('Jersey barriers') dividing the two directions of traffic and making it impossible for most non-flying animals to cross the road. During road expansion or improvement, road ecologists might suggest replacing Jersey barriers with other designs (e.g. vegetated median, centerline rumble strips) that offer traffic safety and do not completely block animal movements [44]. These are examples of road-design specifications that can improve connectivity, even

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Figure 1. Example of an 'extended stream crossing' over a stream in New Brunswick, Canada. Design details will vary but the width of the extended stream crossing should be approximately five times the width of the stream at high water, allowing dry passage of terrestrial animals along its banks. The height should be sufficient to allow passage of the tallest animal for which mitigation is desired, here moose, *Alces alces*. Reproduced, with permission, from L. Fahrig.

Figure 2. Schematic representation of a vegetated overpass on Highway 69 in Ontario, Canada. Early collaboration between planners and researchers led to the design of a 30 m-wide overpass to accommodate the large population of elk, *Cervus elaphus*, and other large mammals present in the area. This overpass and the road were completed in 2012. Reproduced, with permission, from the Ontario Ministry of Transport.

though the road expansion might result in increased traffic. Similarly, in the case of a new road, ecologists involved in the road planning stages might suggest incorporation of measures that would reduce the anticipated impact of the road on connectivity (Figure 2).

Note that, if road planners and engineers were already well informed of wildlife movement issues, ecopassages and other design features for wildlife could be included in the road project without direct involvement of road ecologists in the road planning. However, we suggest that this is generally not the case. Owing to the communication issues discussed above, road planners are largely unaware of road ecology results and suggested best practices and, until that situation changes, the only effective way to ensure incorporation of these in road designs is for ecologists to have direct input during the planning process.

Learning opportunity: road project as a BACI experiment
From the road ecologist's viewpoint, probably the most important reason to be involved early in the planning of a road project (whether a road expansion or a new road) is that such involvement would maximize the possibility of using the road project to conduct a rigorous research project [18]. Such a research project would provide not only information on the effectiveness of ecopassages at the particular site, but also valuable information to inform the design of future ecopassages. Given that researchers cannot conduct independent experiments (i.e. build their own ecopassages), they must rely on collaborations with transportation agencies to study ecopassage effects in conjunction with actual road projects. Planners and engineers would need to allow the researcher to influence the design and placement of ecopassages (e.g. randomized assignment of structure types to ecopassage sites), allowing road

ecologists to test rigorously the effectiveness of different ecopassage types. In such a study, it would be crucial for the road ecologist to begin monitoring animal movements before the project is constructed, to provide baseline data for comparison with similar data collected after the project is in place [18]. Again, such a research project would require collaboration of road ecologists and planners early in the road-planning process.

Communication of results
Finally, communication of information on the effects of ecopassages on wildlife is crucial if wildlife-friendly transportation is to become more common. The road network is relied upon for many reasons. Public involvement in road planning, including discussions of wildlife impacts and mitigation, are crucial for increasing awareness and support for road mitigation. Constructive involvement of the public requires access to research results documenting the success or failure of previous mitigation attempts. Again, early involvement of researchers in the transportation planning process will permit higher-quality research, as discussed above, which in turn would be published in peer-reviewed journals, increasing its accessibility and impact on the road-planning process.

Concluding remarks
Up to now, road mitigation research has mostly languished in a backwater where studies lack scientific rigor, are reported in obscure outlets and are ignored by the larger research community and the road planning community. As the impacts of roads on wildlife populations become more evident [1], road ecology is entering the mainstream of applied ecology. We anticipate that large improvements in the quality of information on road mitigation measures,

such as wildlife ecopassages, are just around the corner. We expect this to increase greatly the impact of road ecology research in both the design of new roads and upgrades and/or repairs of existing roads. This will, in turn, present new opportunities for research, resulting in improvements in knowledge about the effectiveness of ecopassages. In our most optimistic moments, we envision that these research advances will lead to reductions not only in the future impacts of roads on wildlife, but also in current road impacts, and improvements in ecological condition around roads, even as traffic levels continue to increase. In our more realistic moments, we recognize the costs and inherent disincentives for including ecopassages, and rigorous research on their effectiveness, within road improvement and construction projects. Ultimately, legislation requiring incorporation of ecopassages and other mitigations and associated research and monitoring is likely to be necessary.

Acknowledgments

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