Journal of Environmental Management 154 (2015) 48–64

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Experimental study designs to improve the evaluation of road mitigation measures for wildlife

Trina Rytwinski [a,*], Rodney van der Ree [b], Glenn M. Cunnington [a], Lenore Fahrig [a], C. Scott Findlay [c], Jeff Houlahan [d], Jochen A.G. Jaeger [e], Kylie Soanes [b], Edgar A. van der Grift [f]

[a] Geomatics and Landscape Ecology Research Laboratory, Department of Biology, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario, Canada K1S 5B6
[b] Australian Research Centre for Urban Ecology, Royal Botanic Gardens Melbourne, C/-School of Botany, University of Melbourne, 3010 Victoria, Australia
[c] Institute of the Environment & Ottawa-Carleton Institute of Biology, 555 King Edward, Ottawa, Ontario, Canada K1N 6N5
[d] Department of Biology, University of New Brunswick at Saint John, Saint John, 550, New Brunswick, Canada E2L 4L5
[e] Department of Geography, Planning and Environment, Concordia University Montreal, 1455 de Maisonneuve Blvd. W Suite H1255, Montreal, Quebec, Canada H3G 1M8
[f] Alterra, Wageningen University and Research Centre, P.O. Box 47, 6700 AA Wageningen, The Netherlands

ARTICLE INFO

Article history:
Received 15 July 2014
Received in revised form 22 January 2015
Accepted 30 January 2015
Available online 18 February 2015

Keywords:
Population persistence
Road planning
Experimental design
Before-after-control-impact
Effectiveness
Road impacts

ABSTRACT

An experimental approach to road mitigation that maximizes inferential power is essential to ensure that mitigation is both ecologically-effective and cost-effective. Here, we set out the need for and standards of using an experimental approach to road mitigation, in order to improve knowledge of the influence of mitigation measures on wildlife populations. We point out two key areas that need to be considered when conducting mitigation experiments. First, researchers need to get involved at the earliest stage of the road or mitigation project to ensure the necessary planning and funds are available for conducting a high quality experiment. Second, experimentation will generate new knowledge about the parameters that influence mitigation effectiveness, which ultimately allows better prediction for future road mitigation projects. We identify seven key questions about mitigation structures (i.e., wildlife crossing structures and fencing) that remain largely or entirely unanswered at the population-level: (1) Does a given crossing structure work? What type and size of crossing structures should we use? (2) How many crossing structures should we build? (3) Is it more effective to install a small number of large-sized crossing structures or a large number of small-sized crossing structures? (4) How much barrier fencing is needed for a given length of road? (5) Do we need funnel fencing to lead animals to crossing structures, and how long does such fencing have to be? (6) How should we manage/manipulate the environment in the area around the crossing structures and fencing? (7) Where should we place crossing structures and barrier fencing? We provide experimental approaches to answering each of them using example Before-After-Control-Impact (BACI) study designs for two stages in the road/mitigation project where researchers may become involved: (1) at the beginning of a road/mitigation project, and (2) after the mitigation has been constructed; highlighting real case studies when available.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

Roads and traffic have negative impacts on a wide range of animals (reviewed in Trombulak and Frissell, 2000; Spellerberg, 2002; Fahrig and Rytwinski, 2009; Benítez-López et al., 2010; Rytwinski and Fahrig, 2012; van der Ree et al., 2015a). The main focus of road ecology research is to quantify these negative impacts, with the aim of avoiding, minimizing, mitigating, or offsetting negative impacts on individuals, populations, communities, and ecosystems (van der Ree et al., 2011). Options to avoid or mitigate these negative impacts are numerous and have been widely and increasingly implemented around the world (van der Ree et al., 2015b). Examples of mitigation measures include: animal

* Corresponding author.
E-mail address: trytwinski@hotmail.com (T. Rytwinski).

http://dx.doi.org/10.1016/j.jenvman.2015.01.048
0301-4797/© 2015 Elsevier Ltd. All rights reserved.

detection systems, wildlife warning signs, changes in road-verge management, measures to reduce traffic volume, speed and/or noise, temporary road closures, wildlife crossing structures, wildlife fences [e.g., barrier fencing (or exclusion fencing) that prevents wildlife from accessing the road, or funnel fencing that primarily funnels animals to wildlife crossing structures but can also prevent wildlife from accessing the road], wildlife reflectors, wildlife repellents, and modified road designs/viaducts/bridges/lighting (Clevenger and Ford, 2010; Huijser and McGowen, 2010). Wildlife crossing structures (e.g., under- or over-passes: amphibian tunnels, badger pipes, ledges in culverts, land bridges, rope bridges, glider poles), combined with fencing to prevent mortality and funnel wildlife towards crossing structures, have gained considerable recent attention by transportation agencies because they enhance landscape connectivity without affecting traffic flow (van der Grift et al., 2013).

There is compelling evidence that many wildlife species regularly and frequently use crossing structures (reviewed in van der Ree et al., 2007), and that well-designed and maintained fencing greatly reduce rates of wildlife mortality and funnels animals towards the crossing structures (reviewed in Glista et al., 2009). Unfortunately, documenting use of a crossing structure (i.e., 'success' at the individual level) is so far removed from higher level quantities of interest (i.e., population size and persistence), that such studies provide little information as to whether the structure actually mitigates the effect of the road enough to ensure a viable population (van der Grift et al., 2013). Consequently, the influence of these mitigation structures on population viability is unclear for most road-affected species.

Ultimately, we want to be confident that the predicted impact of a road on a wildlife population will be at least partially mitigated by the proposed road design and that the investment in crossing structures and/or fencing is justified. For example, if the mitigation for an endangered species is ineffective such that the population of the target species declines, the road agency must respond and retrofit the road or modify the mitigation structures. In such cases, it is essential that road agencies have reliable evidence to make informed decisions about which feature of the road or mitigation should be implemented or modified and by how much.

Here we identify seven key questions road planners commonly have about crossing structures and/or fencing that for many species and structure types remain largely unanswered at the level of ultimate concern (e.g., population or community) and at the required level of certainty by existing research (Box 1). These questions must be answered not only so that resources for road mitigation are allocated in the most effective manner, but that they indeed have the predicted (desired) effect.

Box 1
Seven key questions road planners commonly have about crossing structures and fencing.

Questions road planners have about mitigation structures:

Question 1
Does a given crossing structure work? What type and size (width, height and length) of crossing structures should we use?

Question 2
How many crossing structures should we build?

Question 3
Is it more effective to install a small number of large-sized crossing structures or a large number of small-sized crossing structures?

Question 4
How much barrier fencing is needed for a given length of road?

Question 5
Do we need funnel fencing to lead animals to crossing structures, and how long does such fencing have to be?

Question 6
How should we manage/manipulate the environment in the area around the crossing structures and fencing?

Question 7
Where should we place crossing structures and barrier fencing?

There are two main reasons why these questions have remained unanswered. First, the existing approach to road mitigation is to simply adopt current best-practice in terms of the type, number, and location of mitigation. While this approach identifies the best known mitigation for installation, it does not explicitly facilitate learning about the effectiveness of mitigation because the mitigation was installed to solve a problem, not generate new information. Second, studies evaluating the effectiveness of mitigation structures have low inferential strength, and, as such, comparatively low predictive power. For example, studies often lack: (1) comparisons between treatment sites (also referred to as 'impact' sites in Before-After-Control-Impact (BACI) study designs (Roedenbeck et al., 2007; van der Ree et al., 2015b)) and control sites (i.e., sites that have not been affected by the treatment – these will vary depending on the question and goals of the road mitigation, but may include e.g., road-free areas, areas with narrow or low-traffic volume roads, unmitigated roads, and/or unmanipulated mitigation measures; see section 5 on experimental designs for more detail); (2) data on population sizes or trends prior to mitigation; (3) replication in both space and time; and (4) randomization of treatment and control sites across the pool of potential study sites. Moreover, many study designs confound mitigation variables (e.g., overpass width, density of shrubs at culvert entrance) such that their independent effects cannot be evaluated (reviewed in van der Ree et al., 2007; Glista et al., 2009). For road agencies to make informed and reliable decisions, we need to improve the rigor of studies that evaluate the effectiveness of mitigation measures.

Ways to improve the quality and impact of road ecology research and monitoring have been previously discussed. Roedenbeck et al. (2007) provided a research agenda for road ecology, identifying relevant questions (e.g., Under what circumstances do roads affect population persistence?, and Under what circumstances can road effects be mitigated?), and specifying a hierarchy of study designs for answering these questions. van der Grift et al. (2013) used the principles outlined in Roedenbeck et al. (2007) to propose a methodological framework for increasing the inferential strength of mitigation monitoring schemes. Lesbarrères and Fahrig (2012) proposed the use of such monitoring schemes as a type of experiment, but they did not suggest associated experimental protocols. van der Ree et al. (2015b) summarises these papers into an accessible format for practitioners. Here, we set out the need and standards for using experimental approaches to road mitigation to improve knowledge on the influence of mitigation structures on wildlife populations. We first demonstrate the need for an experimental (manipulative) approach to road mitigation projects. We then outline the road/mitigation project stages and describe how flexibility in experimental design depends on the stage in the road project at which researchers become involved. We provide experimental approaches to answering each of the questions in Box 1, highlighting real case studies when possible, and we conclude with a discussion of potential issues in using experimentation to evaluate the effectiveness of crossing structures and fencing.

2. Why we need an experimental approach to road mitigation

Most road agencies currently evaluate the effectiveness of mitigation efforts through post-implementation monitoring (van der Ree et al., 2015b). Questions commonly asked with monitoring include: Will a particular species use an underpass to cross the road? and/or Which factors are correlated with the number of crossings? However, the state of road ecology has matured since mitigation structures were first developed, and while monitoring rate of crossing is an important first step, and likely appropriate in certain circumstances, it is no longer enough to simply document the use of a structure by the target animal(s) (van der Grift et al., 2013). In addition, we need to answer questions such as: Is the rate of road mortality sufficiently low and/or the rate of crossing sufficiently high to ensure a viable population? or Which parameter of the road, traffic, or mitigation structure should we modify to improve population viability to an acceptable level? These questions are best addressed with an experimental approach.

The advantage of experimentation is that it can yield stronger inference (if done correctly) and often more efficiently than a non-experimental approach. For example, suppose that to inform future wildlife overpass designs, one wanted to know the relative importance of certain overpass attributes (say, vegetation cover, x_1) compared to others (say, overpass width, x_2). If one had a sample of overpasses that varied in these attributes at which one monitored crossing rates (y), one could address this question by fitting models $y = f(x_1, x_2)$ and estimating the corresponding partial regression coefficients. Doing so, however, would require a comparatively large number of overpasses to get robust estimates of model parameters [e.g., if x_1 and x_2 are both ratio/interval valued, the simplest model with a multiplicative interaction would have $p = 4$ parameters, and assuming one wants $N/p \geq 10$ (the usual rule of thumb), this means $N \geq 40$ overpasses are required]. And parameter robustness notwithstanding, one still has comparatively weak inference because of the correlative study design. By contrast, employing a BACI experimental approach (see Appendix A for a description of general study designs for road mitigation), one could design the study with half the required sample size (e.g., 2 levels for each of x_1 and x_2, with 5 replicates each − yielding $N = 20$ overpasses for a fully factorial design). The result? Stronger inference at lower cost, i.e., greater informational efficiency.

Another reason that an experimental approach is required is that road mitigation can be expensive, particularly when it is retrofitted to existing roads. Transportation agencies often have limited funds to implement and evaluate mitigation measures. For example, under the Provincial Highways Management Division Strategic Plan for the Ontario Ministry of Transportation (MTO), Canada, the report states that at least 75 cents of every construction dollar should be invested directly in bridges and pavements, leaving only 25 cents for all other aspects, including mitigation (B. Carruthers, MTO, pers. comm). The cost of mitigation demands that effective solutions are deployed, and where an effective but cheaper solution is available, it should be adopted. An experiment is the best way to compare possible solutions and determine their relative effectiveness.

The most powerful aspect of experiments is that they efficiently produce new knowledge. For example, if the route of a proposed road project were to intersect a number of approximately equal-sized streams, the current approach to road mitigation is typically to install similar underpasses at each stream crossing. An evaluation of crossing rates may indicate that species X uses the underpasses, but we are unable to say whether larger or smaller underpasses or a different type of mitigation structure would increase the rate of use compared to those installed. Alternatively, if the mitigation were designed as an experiment where, for example, underpasses were installed at a random selection of half of the stream crossings and the remainder installed with extended bridges, we could then explicitly test how structure type affects the rate of use (or better yet, population size). Installation of mitigation measures explicitly in accordance with an experimental protocol, which when possible includes a replicated BACI study design, will increase the understanding of their effectiveness and accumulate new knowledge (Fig. 1). Furthermore, to build mitigation knowledge that can be applied in a variety of situations, we need to move beyond asking whether species X crosses the road at location Z, to broader questions relevant to different species, landscapes, roads and/or road projects (Fig. 2). In this way, each new mitigation experiment will build on the insights obtained from existing knowledge and previous experiment(s), thus continually improving understanding of mitigation effectiveness and increasing predictive power for extrapolating results from one location to another and/or from one species to another. Specifically, if experiments are designed well, information gained in one location or for a particular species can be applied to other locations or species helping to provide ecologically-effective and cost-effective solutions.

3. Road project stages and experimentation

There is a direct relationship between the road/mitigation project stage at which researchers become involved, the ease of experiment implementation, and the knowledge gain at the end of the experiment. If the experiment is designed early in the planning process, a wider range of experiments are possible with some at least having comparatively high inferential strength, broader implications, and greater potential to extrapolate to other locations/species. On the other hand, such experiments will typically require more funds, a longer evaluation time-frame, more political/stakeholder support, and more organization and planning than simpler (and likely less valuable) studies designed late in the planning process. Even when researchers become involved in the early planning stages, there will be limitations on the kind of study that can be implemented; a conceptually feasible experiment is not necessarily practically feasible. For example, the length of a proposed road may be too short for the number of treatment and control sites needed to adequately address the research question. This reinforces the need for researchers and road planners to be in communication at the earliest stages, so that the researcher can identify a set of feasible experiments and select the one that will be the most informative, given the constraints of the road project.

There are typically six stages in the road planning process (Ontario Ministry of Transportation, 2010; U.S. Department of Transportation, 2012; Roberts and Sjölund, 2015). Although their names and scale often vary across agencies and with the size of the project, they are: (1) strategic planning, (2) project development (preliminary design), (3) detailed design, (4) property acquisition, (5) construction, and (6) operation and maintenance. While there are many different process models for building, upgrading, and/or improving a road, here we provide a general description of each stage. In strategic planning, route options are developed and key project goals established. The strategic planning stage usually concludes with the preparation of an investment plan identifying targets for cost, traffic access, safety, and design, but rarely provides targets for environmental or ecological issues (Roberts and Sjölund, 2015). In the project development stage, the transportation project is more clearly defined. This stage includes studies of the environmental impacts of broad transportation alternatives and specific highway improvement options. By the end of the project development stage, there is generally a description of the location and major design features of the project (U.S. Department of Transportation, 2012). In the detailed design stage, engineers undertake surveys, test for soil conditions, determine construction material requirements, and design interchanges, bridges, and

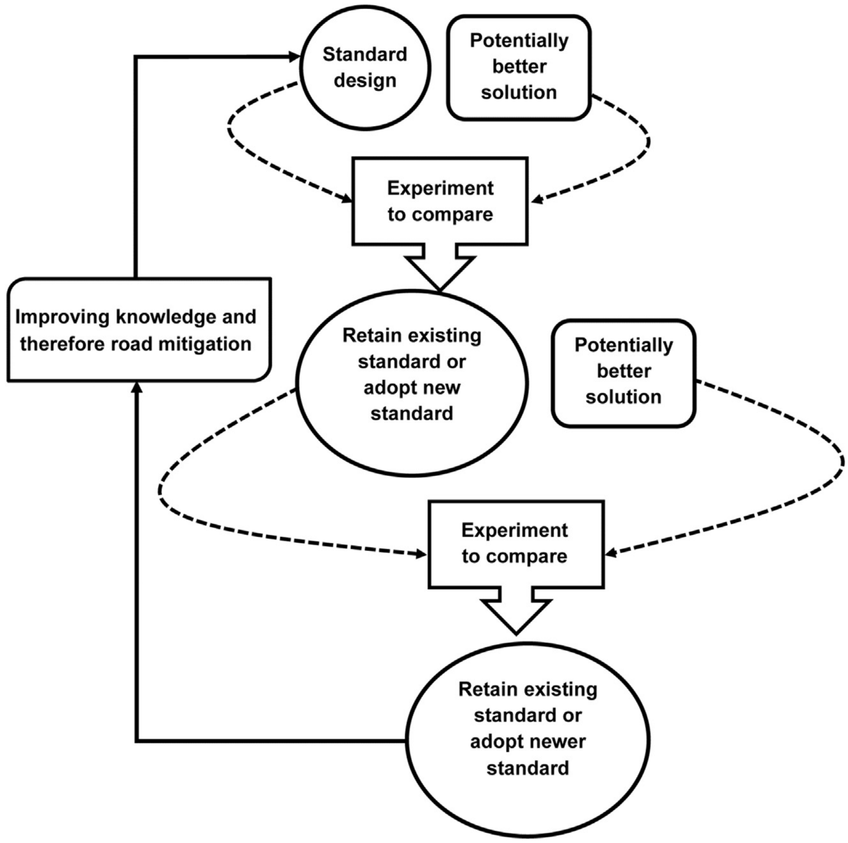

Fig. 1. Flow diagram illustrating the iterative process of improving knowledge through experimentation and, as a result, improving mitigation on the next road project, which is then used as another experiment to further improve mitigation on the next road, and so on. Where possible, a BACI experimental approach should be used in the experiment to compare the current standard with the potentially better solution.

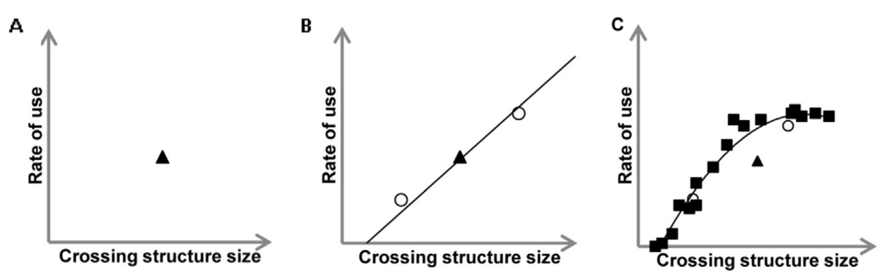

Fig. 2. In this hypothetical example, the rate of use of a crossing structure by wildlife has been monitored over time. In (A) the question was "how often does species X use the structure?" (a normal road agency question), and a single data point has been collected which cannot be extrapolated or generalised to other locations. In (B), the question is slightly broader, and three crossing structures have been monitored, but because the sample size is still insufficient, one might conclude that very large crossing structures will always perform better than smaller ones. With sufficient replication (C), the data show that there is a threshold in the benefit of increasing the size of a crossing structure, beyond which the increasing cost of larger structures would not be justified.

culverts; a comprehensive set of plans is produced during this stage (Ontario Ministry of Transportation, 2010). Once environmental reviews have been approved by government(s), acquisition of land needed for the project can begin. In the final stages, the project is constructed, followed by operation and maintenance activities.

The duration of the road project will depend on many factors, including the jurisdiction(s) involved and complexity of the project, funding availability, property availability, and timing of environmental clearances with permits. The planning, design, and construction of a highway expansion in Canada for example can typically take up to eight or more years, and 10 years or more to build a new highway (Ontario Ministry of Transportation, 2010). To break this down further, the duration of the planning and design stages can take up to 5 years, up to 3 years for environmental assessments, 1.5–5 years for property acquisition, and 5–8 years for construction (Ontario Ministry of Transportation, 2010). Furthermore, these stages may not always happen sequentially.

4. Opportunity for improved experimental design

The flexibility to change components of the experimental design will be influenced by the stage within the road/mitigation project when researchers begin collaborating with road planners (Fig. 3). For a description of general study designs for road mitigation see Appendix A. Here, we define treatment sites as sites where mitigation measures are to be installed or manipulated, and there can

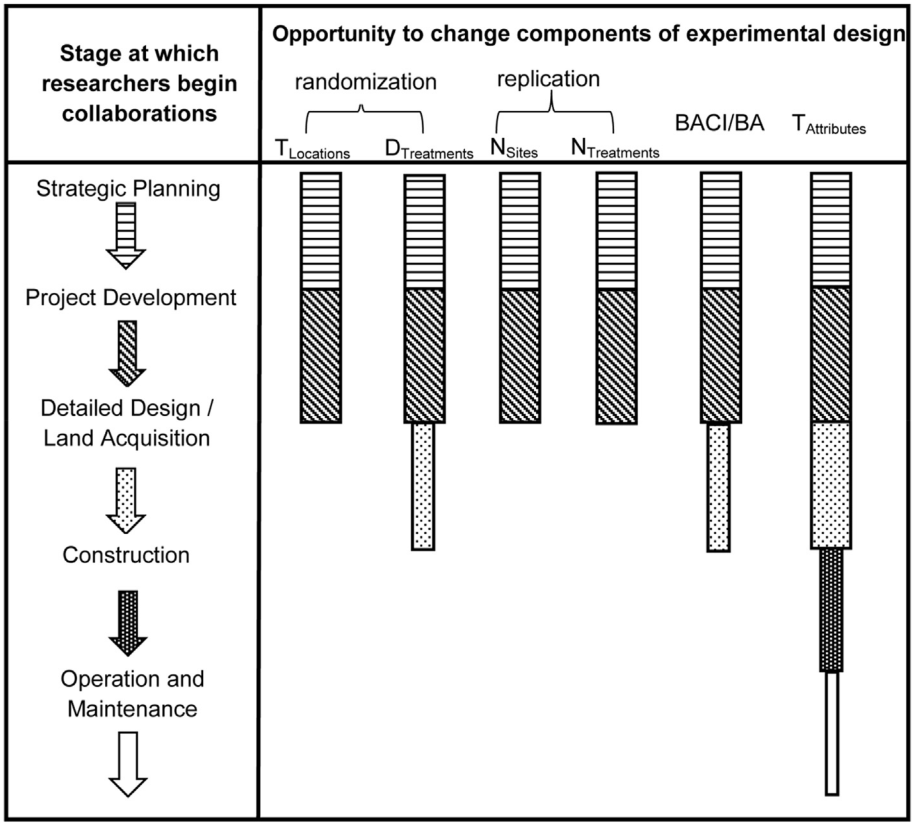

Fig. 3. The flexibility of researchers to change components of the mitigation experimental design depends on the stage of the road/mitigation project in which they become involved. The width of the bars represents the amount of flexibility researchers have in changing components of the experimental design, with wider bars indicating greater flexibility than more narrow bars. Bar design (i.e., dotted, striped etc.) corresponds to the road/mitigation project stage at which researchers begin collaborating with road planners. $T_{Locations}$ = location of treatments (mitigation structures); $D_{Treatments}$ = type of treatment (e.g., barrier fencing, land-bridge, underpass, extended stream crossing); N_{Sites} = number of treatment sites; $N_{Treatments}$ = number of different mitigation treatments; BACI = before-after-control-impact experiment design; BA = before-after experiment design; $T_{Attributes}$ = treatment attributes (e.g., type and height of barrier fencing, type and size of furniture added to land-bridge (trees, boulders), substrate type and size of underpasses and extended stream crossings).

be different types of treatments used in an experiment e.g., barrier fencing, land-bridges, culverts, extended stream crossings (i.e., allowing for terrestrial passage alongside the stream bed), etc. At the strategic planning stage, researchers have a nearly blank canvas to design a mitigation experiment with, potentially, high inferential strength. At this point, within the physical constraints of the project, there is still high flexibility in: (1) randomizing the locations of treatments (mitigation structures) and the types of treatments, and controls among sites; (2) selecting the number of treatment and control sites, and the number of different treatments to be installed; and (3) collecting before data for the measurement of interest (Fig. 3). If researchers begin collaboration with road planners at the beginning of the project development stage, they retain the same level of flexibility for all components of the experimental design as if they begin at the strategic planning stage; however, they likely have lost up to three years of time for collecting 'before' data (Fig. 3).

The length of time required to evaluate mitigation effectiveness before (and after) construction will depend on the ecological outcome of interest (e.g., population abundance, number of road-kills, movement, etc.) and the characteristics of the focal species. In general, for a long-lived, highly mobile species, the collection of before data would be required over a longer period to assess a change in population abundance than that required to detect a change in movement (see van der Grift et al., 2013 for further details on appropriate sampling schemes and possible ecological outcomes of interest). At the end of the project development stage, however, the road/mitigation project is more clearly defined with the location and major design features already selected. Researchers entering into the planning process at the beginning of the detailed design stage no longer have flexibility in randomizing the locations of the treatments, but they may have some flexibility in randomizing treatments among the selected mitigation locations. Furthermore, researchers no longer have the ability to select the number of treatment sites as well as the number of different mitigation treatments (i.e., replication) since the number of treatment locations will have been selected prior to the detailed design stage (Fig. 3). For example, if ten locations have been pre-selected for the installation of mitigation structures (during the project development stage), researchers cannot select five different treatment types to evaluate mitigation effectiveness since the number of replicates per treatment (i.e., 2 replicates) would not be sufficient to provide robust conclusions. Flexibility in collecting 'before' data for BACI or BA (Before-After) experimental designs (see Appendix A) may also be very limited at this stage because if construction is imminent it will be difficult to obtain a sufficiently long time sequence of before data, to make robust comparisons with the 'after data' (Fig. 3). However, if the time between the start of the detailed design stage and construction is long enough (e.g., if land acquisition is expected to take longer than normal), it may still be possible to obtain adequate before data even if the researcher only becomes involved at the beginning of the detailed design stage. Once construction begins, the attributes of the mitigation structures (e.g., type and/or height of fencing, substrate type and size of underpasses) of the pre-selected mitigation treatments (e.g., fencing, underpasses), become highly constrained (Fig. 3). For example, only minor attributes such as reducing the size of a wildlife underpass or changing the substrate type can potentially be modified. After construction, only mitigation attributes can be experimentally manipulated (e.g., mowing, addition of coarse woody debris, manipulating (reducing) underpass width).

5. Experimental designs

In this section, we describe potential experimental approaches for each of the research questions in Box 1 and provide, when possible, case studies highlighting mitigation experiments that have been conducted or are proposed. More specifically, we provide example BACI study designs for two stages in the road/mitigation project where researchers may become involved: (1) at the beginning of a road/mitigation project i.e., project development stage, and (2) after the mitigation has been constructed i.e., operation and maintenance stage (post-mitigation). We chose these two project stages as they represent the extremes in terms of the amount of opportunity and/or flexibility in designing high-inference studies, with experiments conducted at the project development stage having more flexibility and therefore higher potential inferential strength than post-construction experiments. To reiterate, to conduct mitigation experiments, a high level of collaboration among researchers and transportation agencies will be required at all stages in the road project. Furthermore, researchers will need to design the experiments within the constraints of the road project.

BACI mitigation experiments at the project development stage can be carried out on both new and existing roads, resulting in two design situations: (1) the road and mitigation are to be constructed simultaneously; or (2) the mitigation is to be constructed on an existing road. For new roads, researchers collect data on an outcome of interest before and after the road and mitigation are installed at treatment and control sites. For existing roads, researchers collect data on a measurement of interest before and after the mitigation is installed on an existing road at treatment and control sites. In the case of mitigation retrofits of an existing road, usually only a limited range of BACI experiments are possible, such as evaluation of fencing, or manipulation or modification of existing mitigations (e.g., reducing underpass width or height, reducing fence permeability, addition of coarse woody debris to underpasses, or temporarily closing/opening existing crossing structures). New crossing structures are only occasionally constructed on existing roads, primarily due to the higher costs associated with retrofitting an existing road compared to the costs of building new roads and mitigation simultaneously. However, this is likely to change in North America and Europe as the rate of construction of new roads slows and shifts to a greater focus on expanding the capacity of the existing network and repair of failing infrastructure providing an opportunity for a wide range of BACI mitigation experiments on existing roads. For all mitigation experiments, two sets of replicated sites are required: (1) treatment sites where mitigation measures are to be installed or manipulated, and (2) control sites where sites are not affected by the treatment. To evaluate mitigation effectiveness, treatment sites are compared to control sites. The type of control site will vary depending on the question and goals of the road mitigation, and may include road-free areas, areas with narrow or low-traffic volume roads, unmitigated roads, and/or unmanipulated mitigation measures (Fig. 4) (also see van der Grift et al., 2013).

5.1. Question 1: Does a given crossing structure work? What type and size (width, height and length) of crossing structures should we use?

This question is frequently posed by road planners. However, to design an experiment to answer it, we first need to define ‘work’. The general question has to be translated into goals that are highly specified, or SMART: Specific, Measurable, Achievable, Relevant and Time-framed (van der Ree et al., 2007). There are generally two potential objectives in road mitigation goals: (1) no net loss (i.e., road impacts will be fully mitigated), and (2) limited net loss (i.e., a limited road impact will be accepted) (van der Grift et al., 2013). Proper evaluations of the extent to which the full effect of roads have been mitigated (i.e., no net loss/full mitigation) can only be made by comparing treatment sites to road-free control sites (Fig. 4).

Proper evaluations of the extent to which population size improves (i.e., limited net loss/partial mitigation) can only be made by comparing treatment sites to mitigation-free control sites (i.e., how much better (or worse) is the mitigation treatment than having no mitigation at all?) (Fig. 4). Proper evaluations of the extent to which a modification to an existing mitigation improves population size in comparison to the existing unmodified mitigation can only be made if modification-free control sites are included (i.e., how much better (or worse) is the modified mitigation than the existing mitigation?). Road planners and researchers need to decide on mitigation targets early in the planning process to ensure the study design (e.g., type of control sites) and data collected can rigorously address the questions of interest.

In practice, question 1 needs to be rephrased to include the specific objectives of the particular mitigation. For example, if it was feared that a proposed road would impact species X by reducing connectivity between its breeding and foraging habitat, the researcher and road planner may ask “Do crossing structures allow sufficient movement of species X such that the population level after construction remains similar to road-free conditions (i.e., no net loss)?” Furthermore, if we suspect that crossing structure type and/or size will affect use by species X, we should explicitly attempt to incorporate these factors into the design so that the mitigation experiment tests how structure size and type affect the rate of use. Question 1 can be most effectively answered using a BACI experiment designed at the project development stage. The goal would be to maximize the information derived by having as many different mitigation treatments as possible (i.e., types and sizes of crossing structures), while still ensuring sufficient replication of each treatment (Fig. 5). For example, if many potential mitigation sites are available, the researcher could include wildlife underpasses and overpasses in a range of sizes and shapes (e.g., narrow overpasses vs. wider land bridges, box culverts vs. arched culverts etc.), yet maintaining the required degree of replication. To address the broader question as to whether a given mitigation structure works at all, a second control type will need to be added to this study design at unmitigated road sites (mitigation-free). This would allow researchers to determine the relative effect of each treatment on population size compared to roads that are built without crossing structures (i.e., how much better are different types and sizes of crossing structures at restoring or maintaining populations than roads with no crossing structures at all?). In the example figures (Figs. 5, 7–10, 12, 13, and Appendix B–E), we include three or four replicates of each mitigation treatment. Note we are not suggesting this level of replication is sufficient for all experiments. The number of required replicates will vary depending on the measurement of interest, the species of concern, and the location (e.g., habitat type, topography) (see van der Grift et al., 2013). Furthermore, in these same example figures, we provide

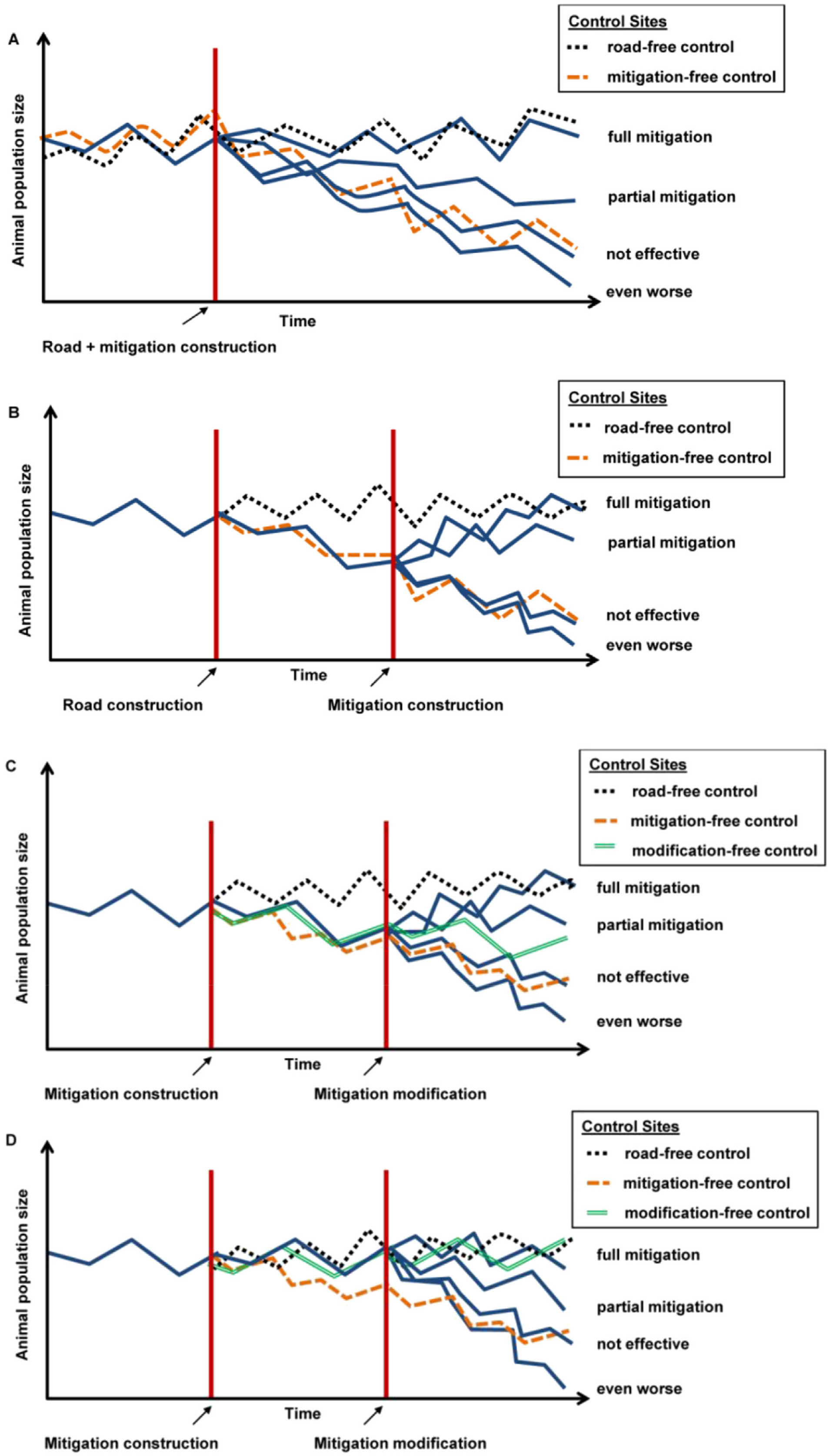

Fig. 4. Illustration of changes in animal population size over time (blue solid lines) when evaluating the effectiveness of road mitigation measures where (A) the construction of the road and mitigation take place simultaneously, (B) there is mitigation of an existing road, and (C and D) there is modification (or manipulation) to existing mitigation. In all panels, it

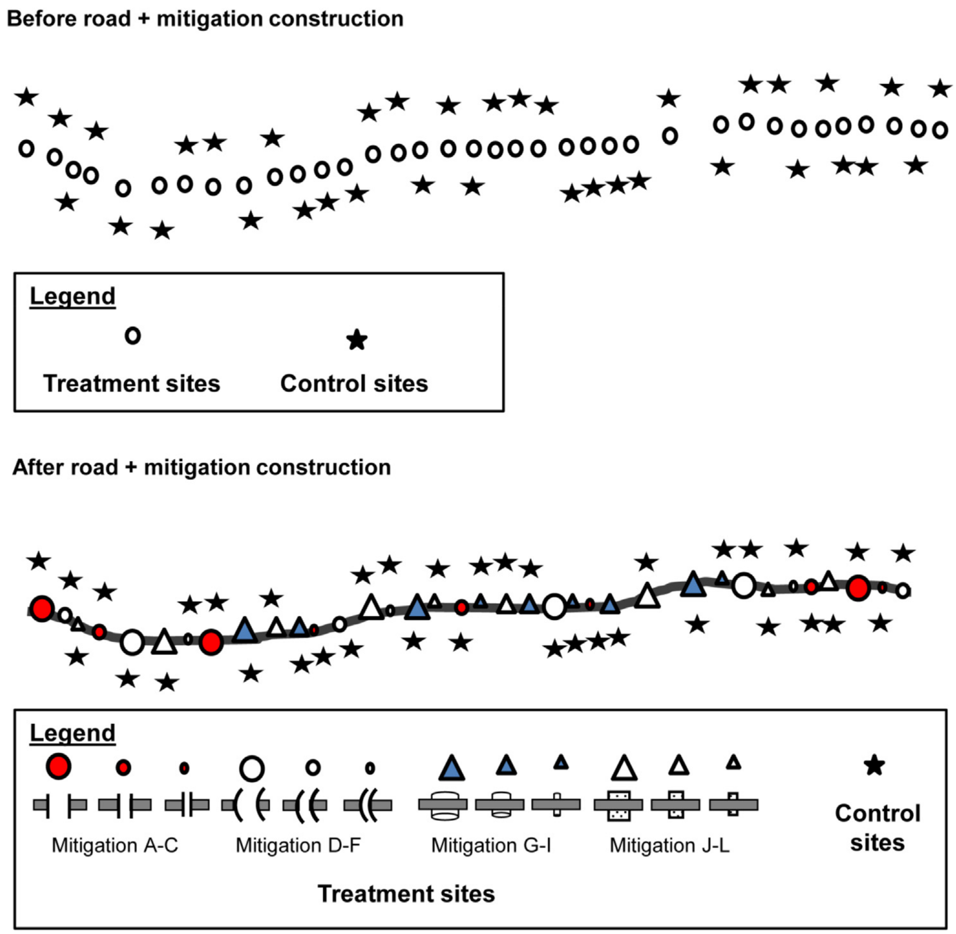

Fig. 5. BACI experimental design at the project development stage for Question 1: Does a given crossing structure work, and if so, what type and size (width, height and length) of crossing structures should we use? Specific question: What type and size of crossing structure allows sufficient movement of species X such that the population size remains the most similar to conditions at road-free areas? In this example, the road and mitigation structures are constructed simultaneously. Data (e.g., relative population size) are collected at treatment and control sites before and after the road and mitigation structures are constructed. Two different overpass types (mitigation A–F) and two different underpass types (mitigation G–L), each of three different sizes are constructed. For each mitigation type, there are three replicates and all treatment sites are randomly located along the road segment while control sites are in road-free areas outside of the road effect zone.

an example measurement of interest i.e., relative population size, to be collected at treatment and control sites before and after the road and mitigation structures are constructed/modified. As suggested by van der Grift et al. (2013), the most informative measurement of interest is the trend over time in the size (or density) of the local population since this is most closely related to the outcome of real concern i.e., population viability. Note we are not suggesting that this is the only measurement of interest that can be collected. The type of data collected will depend on the species of concern, time and budget of the project, and whether or not the road and mitigation are constructed simultaneously. For example, road-kill counts cannot be collected before construction of a project where the road and mitigation are built simultaneously since there is no road for animals to be killed on at this stage. In addition, we do not include a spatial scale to our experimental design figures as these are intended to be example protocols to which modifications can be made. As noted by van der Grift et al. (2013), it is difficult to provide a guideline to determine the spatial scale of a study since the size of the road effect zone varies depending on the road effect being mitigated, the focal species, and the local habitat and topography.

is assumed that the species of interest is negatively impacted by roads. In general, for panels A–C, there are four scenarios after mitigation or modification to mitigation: (1) the mitigation/modification measures are 100% effective at mitigating road impacts and population size remains similar (A) or increases (B and C) to the level of the road-free control sites (i.e., no net loss/full mitigation); (2) the mitigation/modification measures partially mitigate road impacts and population size increases compared to the mitigation-free control sites (i.e., sites where the road is present but without mitigation) but does not reach the level of the road-free control sites (i.e., limited net loss/partial mitigation); (3) the mitigation/modification measures are not effective and population size remains similar to the mitigation-free control sites; and (4) the mitigation/modification measures are not effective and even worsen the situation by reducing population size compared to the mitigation-free control sites. Proper evaluations of the extent to which the full effect of roads have been mitigated (i.e., full mitigation) can only be made if road-free control sites are included (black dotted lines). Proper evaluations of the extent to which population size improves (i.e., partial mitigation/limited net loss) can only be made if mitigation-free control sites are included (orange dashed line) (i.e., how much better (or worse) is the mitigation/modification measures than no mitigation at all?). Proper evaluations of the extent to which a modification to an existing mitigation improves population size in comparison to the existing unmodified mitigation can only be made if modification-free control sites are included (green double lines) (i.e., how much better (or worse) is the modified mitigation than the existing mitigation?). Panel D depicts the situation where the existing mitigation is currently fully mitigating the effects of roads but researchers want to know if modification(s) made to the existing mitigation (i.e., reducing underpass width) could be as effective (and likely cheaper) (e.g., Do we need underpasses as big as they currently are or are more narrow underpasses as effective as the existing wide underpasses?). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

For example, for a highly mobile species, the distance between treatment and control sites would likely be greater than for a less mobile species to ensure spatial independence (see van der Grift et al., 2013 for more details on selecting the appropriate spatial scale of the study). Therefore, certain elements of our example study designs may need to be modified to address individual projects.

Post-mitigation BACI experiments (initiated at the operation and maintenance stage) are possible as well if there is sufficient opportunity for replication. For example, existing crossing structures can be monitored before and after experimentally manipulating the sizes of the structures (i.e., narrowing structure width or height) and comparing those manipulated sites with unmanipulated (control) sites (Appendix B; Fig. 4D).

5.1.1. Case study 1

A new transportation corridor (GTA West) is being planned (2014) in southern Ontario, Canada. The planned corridor is a freeway with ≥4 lanes and is currently in Stage 2 of planning and environmental assessment. The Ontario Ministry of Transportation (MTO) has committed to working with members of the Ontario Road Ecology Group (OREG) and regulatory agencies to assess the viability of collaborating on a wildlife passage research project. OREG began communication with MTO in late 2008 for consideration of a BACI mitigation experiment on the GTA West freeway. The proposed experiment includes four treatment types: (1) extended stream crossings (i.e., allowing for terrestrial passage alongside the stream bed) without funnel fencing, (2) culverts without funnel fencing, (3) extended stream crossings with funnel fencing, and (4) culverts with funnel fencing. The mitigation would be installed where streams intersect the highway and each mitigation site would be paired with a randomly allocated control site located outside the road effect zone. Treatment type would be randomly allocated to stream crossings and all treatments would be replicated. This project would be the first of its kind, providing the opportunity to collect population trend data over time both before and after construction, on a range of wildlife species, to determine which, if any, mitigation will be effective at maintaining populations at pre-road conditions.

5.1.2. Case study 2

The Squirrel Glider (*Petaurus norfolcensis*) is an arboreal marsupial from eastern Australia whose primary mode of travel is by gliding between trees. Many populations are at risk of extinction because of extensive clearing of habitat for agriculture and urbanisation. In recent years, numerous road projects have further threatened the species, because treeless gaps >30–40 m in length can restrict glider movement (van der Ree and Bennett, 2003; van der Ree et al., 2003). However, the ability to assess and mitigate the impact of roads and traffic on Squirrel Gliders was hampered by a lack of information (but see van der Ree, 2006). Therefore, researchers from The Australian Research Centre for Urban Ecology, The University of Melbourne and Monash University, in partnership with VicRoads and the Australian Research Council, set up a BACI experiment to evaluate the effect of a freeway and subsequent mitigation on the movement, gene flow and survival rates of Squirrel Gliders. Capture-mark-recapture surveys, radiotracking and genetic analyses were conducted along the existing 4-lane divided Hume Freeway in rural south-eastern Australia, including sites with vegetated medians (treeless gap across the road < 20 m), unmitigated sites (gap > 50 m), and control sites away from the freeway (gaps < 15 m). Treatment and control sites were identical with the exception that the road at treatment sites was large, with higher traffic volumes and larger gaps than the road at control sites. Radiotracked gliders rarely crossed the freeway at unmitigated sites (van der Ree et al., 2010) and the survival of gliders at the freeway was approximately one third of those at control sites (McCall et al., 2010). Three glider poles and two rope bridges (Fig. 6) were then installed at sites where the treeless gap across the freeway exceeded 50 m. After mitigation, Squirrel Glider movement across the freeway at mitigated sites increased and matched sites with vegetated medians, while the unmitigated freeway remained a barrier. However, movement at all treatments – glider poles, rope bridges and vegetated medians – was still lower than across the narrow gap at control sites (Soanes et al., 2013), indicating that mitigation facilitated road-crossing, but did not fully restore it. The benefit of this study design, where poles and rope bridges were retrofitted to an existing road, allow careful measurement of the effectiveness of mitigation without the added complication of dealing with a simultaneous road expansion. The research is continuing, and includes a post-mitigation analysis of survival rates and an assessment of gene flow before and after mitigation.

5.2. Question 2: How many crossing structures should we build? I.e., how far apart should crossing structures be?

This question can be answered using a BACI experiment planned at the project development stage, if the proposed road is long enough to incorporate different road sections with different numbers of crossing structures per section. The proposed road would be divided into equal-sized zones to which researchers allocate different numbers of crossing structures (Fig. 7). Road zones should be far enough apart to ensure spatial independence, which will be influenced by the movement patterns of the target species. Ideally there should be replicate zones containing the same number of structures for each treatment (number of structures). This experimental design would be logistically very difficult to implement because of the length of road required to incorporate multiple segments, each long enough to contain multiple crossing structures, while being as similar as possible.

An alternative study design would be a post-mitigation construction BACI experiment on a road section with a sufficient number of mitigation structures. Random subsets of the structures could be temporarily closed to manipulate the effective number of crossing structures on the road (Appendix C). Data on population size (or other outcomes of interest) would be first collected at control and treatment sites before any structures are temporarily closed. Then, for example, at time 1, half the structures could be randomly selected to be closed and the populations would be measured again at the control and treatment sites. At time 2, an additional 25% of remaining open structures could be then closed, reducing the number of open structures to 25% of the total number of existing structures. The populations would be again measured at both control and treatment sites. The duration of pre-, during- and post-closure monitoring and the duration of the treatment itself will depend on the level of acceptable risk to the species of concern and the likely time for an effect to be observed.

5.3. Question 3: Is it more effective to install a small number of large-sized crossing structures or a large number of small-sized crossing structures?

A BACI experimental approach planned at the project development stage is the only possible option for addressing this question. As with question 2, the proposed road would be divided into equal-sized zones to which researchers allocate different numbers of crossing structures (Fig. 8). The number of replicates possible will depend on the total length of the proposed road. Similar to the previous example, this experiment will be very difficult to implement as it requires a long road, with sites as similar to each other as

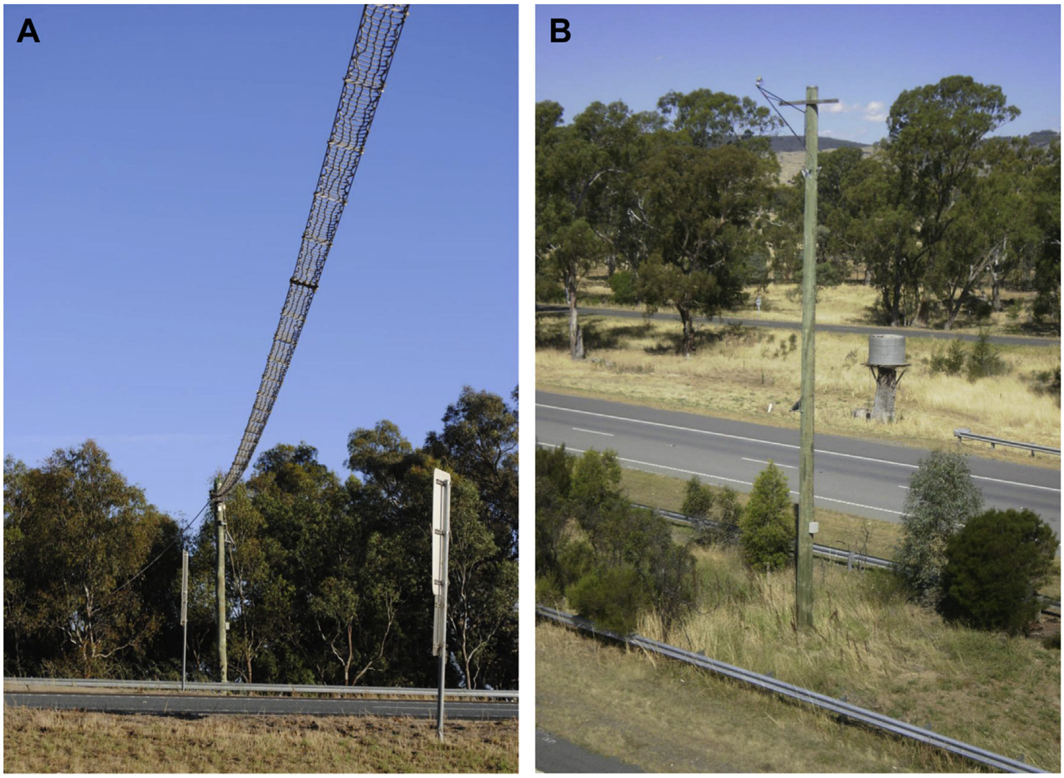

Fig. 6. Mitigation structures installed in a BACI experiment for case study 2. (A) Rope bridges and (B) glider poles installed along the Hume Freeway in south-east Australia to allow Squirrel Gliders to safely cross the freeway. Photos: R. van der Ree.

possible, and the ability to install many mitigation structures.

5.4. *Question 4: How much barrier fencing is needed for a given length of road?*

Similar to crossing structures, road planners also have questions about the effectiveness of barrier fencing that prevents wildlife from accessing the road, for example, how much fencing should there be for a given length of road. A BACI experiment where the proposed road would be divided into equal-sized zones to which researchers randomly allocate different lengths of fencing would be most effective (Fig. 9). The number of different possible treatments will depend on the total length of road planned and the project budget. Depending on the design of the fence (e.g., for amphibians vs. ungulates) and the terrain, this design is logistically easy to implement as an experiment, and as such is highly recommended. Furthermore, this experiment could be done at any time.

5.5. *Question 5: Do we need funnel fencing to lead animals to crossing structures, and how long does such fencing have to be?*

This question would be most effectively addressed at the project development stage where the road and mitigation measures are to be constructed simultaneously. A potential study design might, for example, include eight treatments involving combinations of two different crossing structure types (e.g., over- and under-pass), each with three different fencing lengths extending out from the crossing structures (e.g., long, medium, and short) (Fig. 10). Two of these eight treatments should include the two different crossing structure treatments without any fencing to compare with the fenced treatments (Fig. 10).

This question might also be at least partially addressed experimentally using a post-mitigation construction BACI design. For example, existing crossing structures can be monitored before and after installing funnel fencing of varying lengths and comparing those treatment sites with control sites (Appendix D).

5.5.1. *Case study 3*

Along a 24-km section of the St. Laurence Islands Parkway in eastern Ontario (near Saint Lawrence National Park), Canada, Cunnington et al. (2014) conducted a BACI post-construction experiment by temporarily modifying existing culverts to determine whether underpasses and/or funnel fencing reduce road mortality in anurans (frogs and toads). Study predictions were: (1) if the culverts alone reduce road mortality, than mortality should increase when anurans are not allowed to enter them (culverts with grates blocking their openings), and (2) if fencing is the key to effectiveness, mortality should decrease when fencing is placed on either side of culverts. In 2009, two modifications (treatments) were made to 10 of 20 existing culverts: (1) six culverts were grated preventing anurans from entering the culverts and (2) four culverts were left open but were fenced on either side (Fig. 11). Road kill surveys were conducted before (2008) and after culvert modifications (2009 and 2010). Ten control sites were selected at roaded sites where culverts were present but that had no grates or fencing to compare to treatment sites.

5.6. *Question 6: How should we manage/manipulate the environment in the area around the crossing structures and fencing?*

This question can be addressed at the operation and maintenance stage. A BACI experiment can be designed wherein different aspects of the crossing structure microhabitat are altered or added (e.g., manipulating tree cover, digging ponds, mowing vegetation

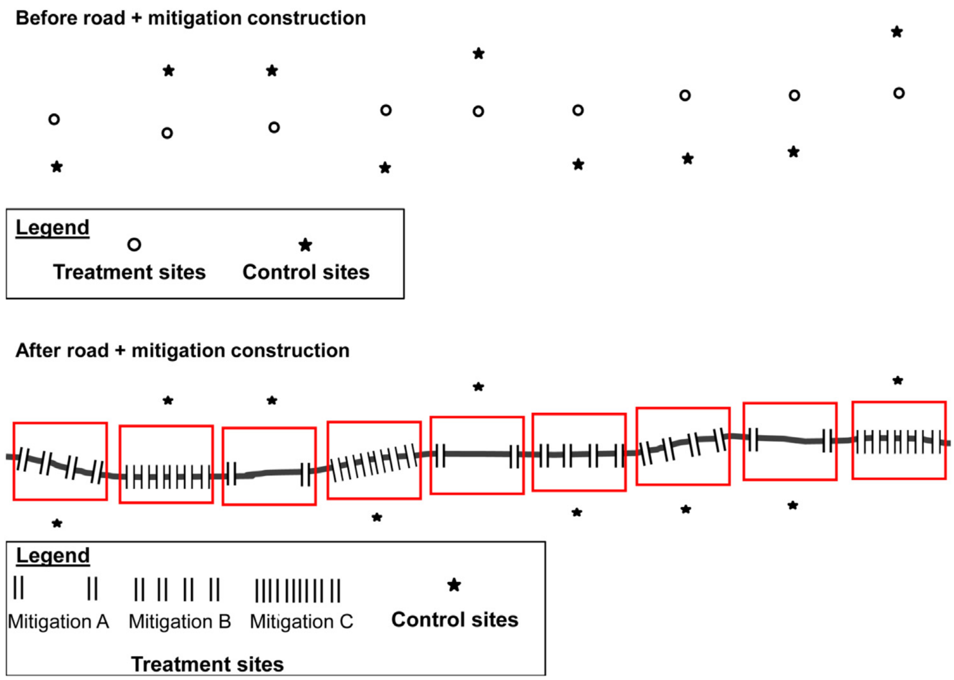

Fig. 7. BACI experimental design at the project development stage for Question 2: How many crossing structures should we build? I.e., how far apart should crossing structures be? Specific question: For a given length of road, what distance between crossing structures allows sufficient movement of species X such that the population size remains most similar to road-free conditions? In this example, the road and mitigation structures are constructed simultaneously. Data (e.g., relative population size) are collected at treatment and control sites before and after the road and mitigation structures are constructed. The proposed road would be divided into equal-sized zones (red boxes) to which researchers randomly allocate different numbers of crossing structures. Here three different road sections with 2, 4, 6 crossing structures (i.e., Mitigation A, B, or C) per section are constructed. For each of the three treatments there are three replicates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

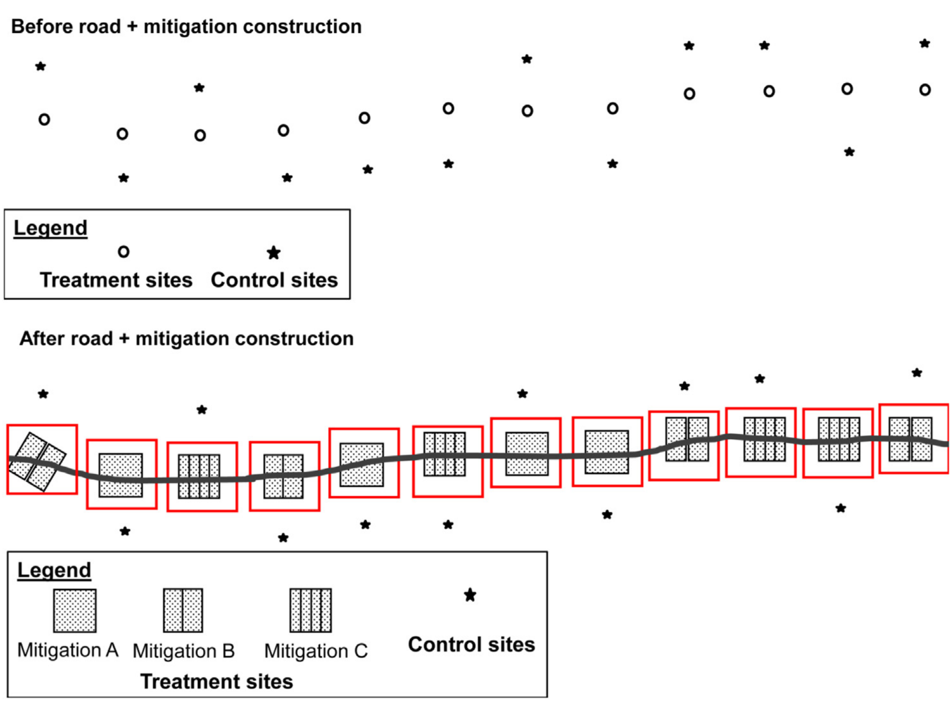

Fig. 8. BACI experimental design at the project development stage for Question 3: Is it more effective to install a small number of large-sized crossing structures or a large number of small-sized crossing structures? Specific question: For a given mitigated road length, what size and number of crossing structures allows sufficient movement of species X such that the population size remains the most similar to road-free conditions? In this example, the road and mitigation structures are constructed simultaneously. Data (e.g., relative population size) are collected at treatment and control sites before and after the road and mitigation structures are constructed. The proposed road would be divided into equal-sized zones (red boxes) to which researchers randomly allocate different numbers of crossing structures. Here three different road sections with different numbers and sizes of crossing structures (i.e., 1 large, 2 medium, 4 small) per section are constructed. For each of the three treatments there are four replicates. Other variants of this design could include also having zones that contain a mixture of different sizes of crossing structures (e.g., 1 large, 2 small). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

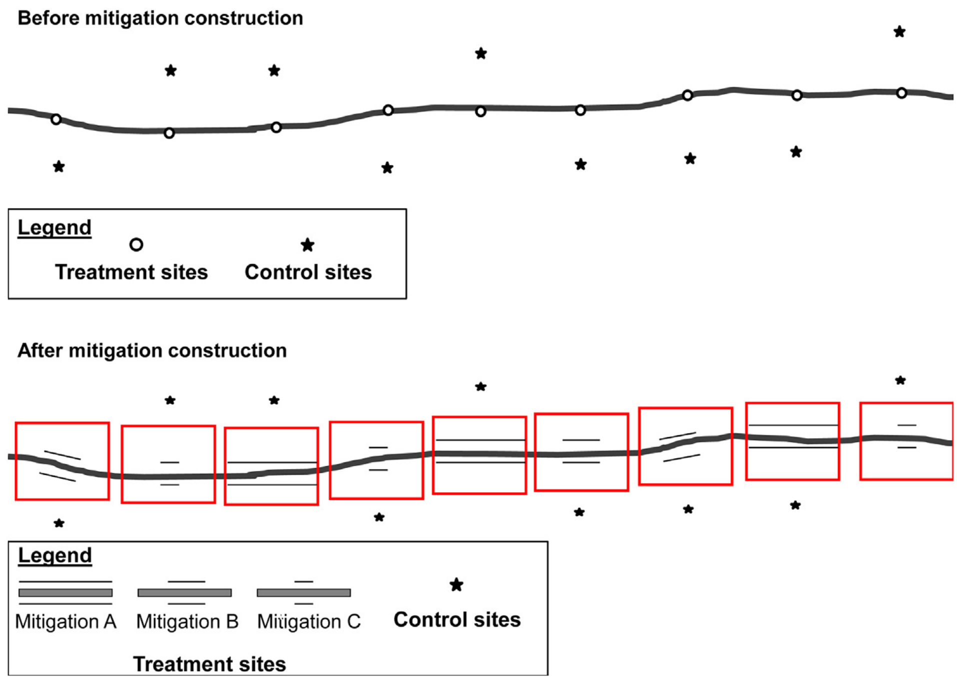

Fig. 9. BACI experimental design at the project development stage for Question 4: How much barrier fencing is needed for a given length of road? Specific question: For a given length of road, what proportion of the road should be fenced to reduce road mortality of species X such that the population size remains the most similar to conditions at road-free areas? In this example, the fences are constructed on an existing road. Data (e.g., relative population size) are collected at treatment and control sites before and after the fences are installed. The proposed road would be divided into equal-sized zones (red boxes) to which researchers randomly allocate different lengths of fencing. Here three different road sections with different proportions of fenced road (i.e., 100%, 50% or 25%) per section are constructed. For each of the three treatments, there are three replicates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

around underpass openings or along fencing etc.). These types of experiments are relatively easy to implement. For example, coarse woody debris can be added to half of the existing crossing structures and the data before and after the manipulation compared to equivalent data taken at unmanipulated sites (Fig. 12). However, designs using existing crossing structures require that the

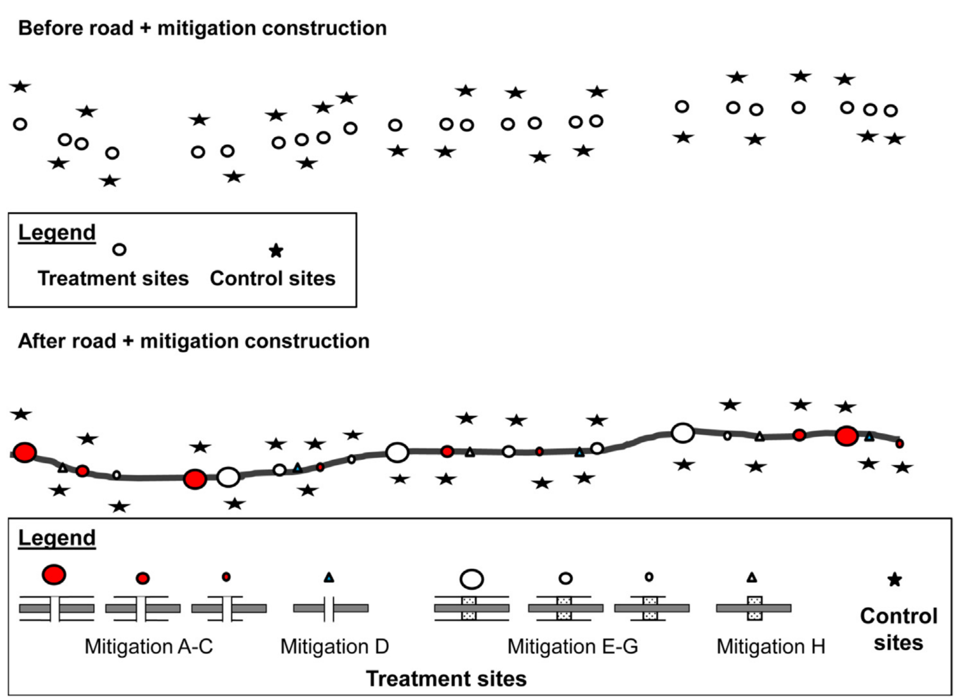

Fig. 10. BACI experimental design at the project development stage for Question 5: Do we need funnel fencing to lead animals to crossing structures, and how long does such fencing have to be? In this example, the road and mitigation structures are constructed simultaneously. Data (e.g., relative population size) are collected at treatment and control sites before and after the road and mitigation structures are constructed. Here two different crossing structure types (e.g., over- and under-pass), each with three different fencing lengths (e.g., long, medium, and short). Two of the eight treatments include an overpass (mitigation D) and underpass (mitigation H) without any fencing. For each treatment, there are three replicates and all treatment sites are randomly located along the road segment while control sites are in road-free areas outside of the road effect zone.

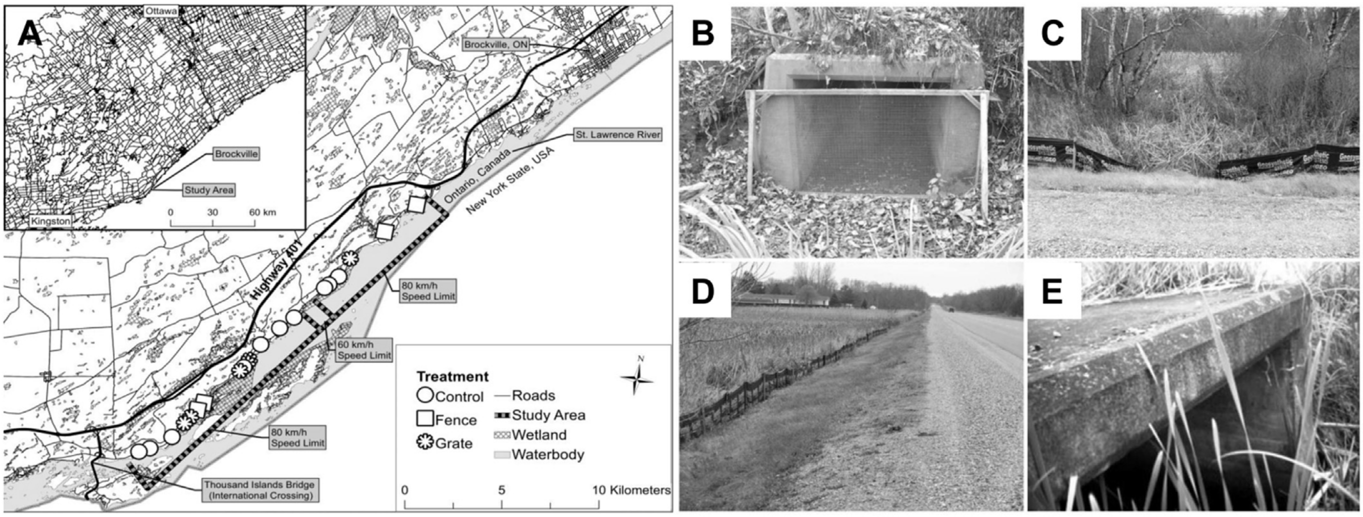

Fig. 11. (A) BACI post-construction experimental design for case study 3 along the St. Laurence Islands Parkway in eastern Ontario, Canada. Two treatment types were randomly allocated to twenty existing culverts along a 24-km road section: (B) grated culverts (n = 6) and (C and D) fenced open culverts (n = 4). Road kill survey data were compared before and after the mitigation modifications were installed at treatment sites and (E) control sites (unmodified culverts n = 10). Modified from Cunnington et al. (2014). Reprinted with permission from © 2014 Ecoscience (ECO-3673).

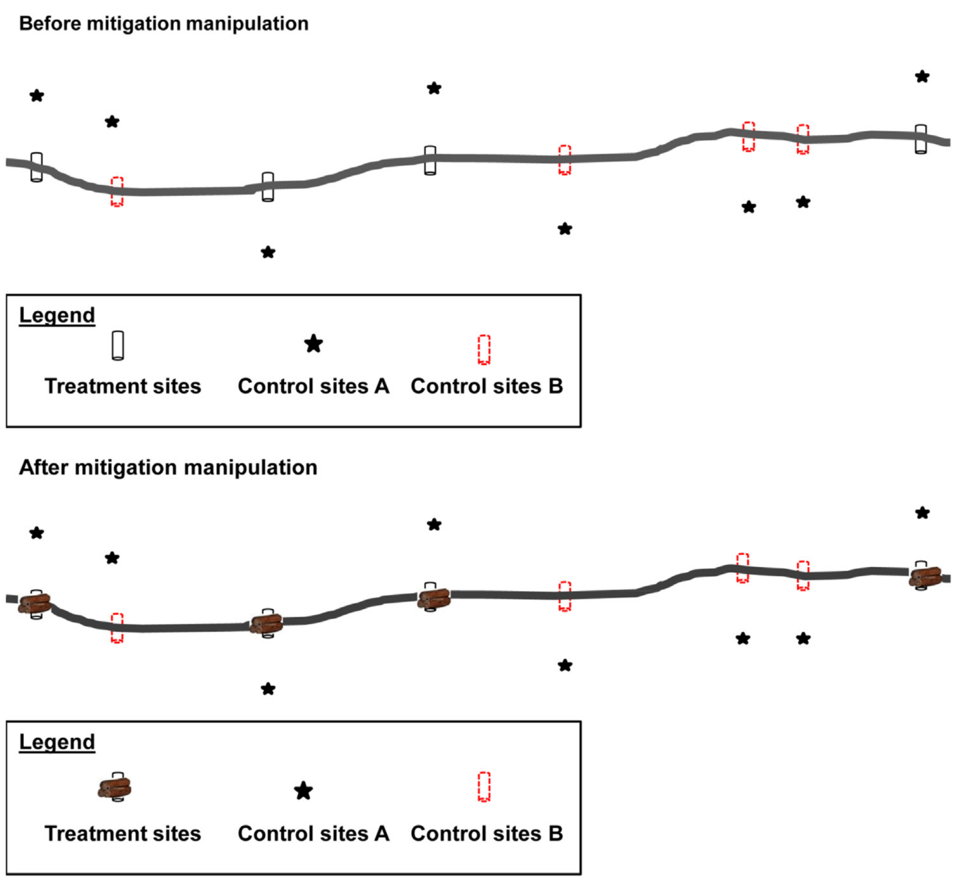

Fig. 12. BACI experimental design post-mitigation construction for Question 6: How should we manage/manipulate the environment in the area around the crossing structures and fencing? Specific question: Does the addition of coarse woody debris in culverts allow movement of species X such that the population size increases after the manipulation in comparison to the unmanipulated culverts? In this example, existing culverts are monitored (e.g., relative population size) before and after adding coarse woody debris to half of the randomly selected culverts. The unmanipulated culverts (control sites B) act as a second control type.

structures are relatively similar to each other or can be grouped into types.

Another common question related to managing the environment is how we should manage co-use of crossing structures (i.e., wildlife, and humans or domestic animals) (van der Ree and van der Grift, 2015). A potential post-construction BACI approach for this question can involve temporarily opening crossing structures to people and/or domestic animals (Appendix E). Another option here could be to experiment with the rate of use of humans or domestic animals (e.g., 5 vs. 500 vs. 5000 users per day) instead of opening and closing the crossing structures.

5.6.1. Case study 4

It has been previously suggested that some taxa, such as small mammals, amphibians, reptiles, and many insects, often avoid open areas because they require cover (e.g., live vegetation, tree stumps, branches, or rocks) to reduce predation risk and because of the microhabitat it provides (e.g., temperature, moisture). In response to the lack of research on modifying crossing structures with coarse woody debris, Connolly-Newman et al. (2013) investigated the effect of cover on the abundance and movements of small mammals in ten large mammal underpasses along U.S. Hwy 93 North on the Flathead Indian Reservation, Montana, USA. Connolly-Newman et al. placed cover (dead tree limbs) inside five of the ten underpasses, while the remaining five underpasses served as control sites. Small mammal track tubes recorded abundance in and around the ten structures before and after underpass modification, thereby permitting inferences about the effects of the modification. More specifically, with only modification-free control sites, Connolly-Newman et al. (2013) can only address the questions: how much better (or worse) is the modified mitigation than the existing mitigation?

5.7. Question 7: Where should we place crossing structures and barrier fencing?

The placement of crossing structures and barrier fencing is believed to be important to mitigation efficacy (Clevenger and Ford, 2010). Wildlife crossing structures and fencing are typically located where animals naturally encounter roads, e.g., along streams or rivers, within a valley, and/or in areas that are vegetated, or at observed road mortality hotspots or landscape variables associated with the hotspots. For example, if animals tend to move along riparian corridors, placing mitigation measures where watercourses

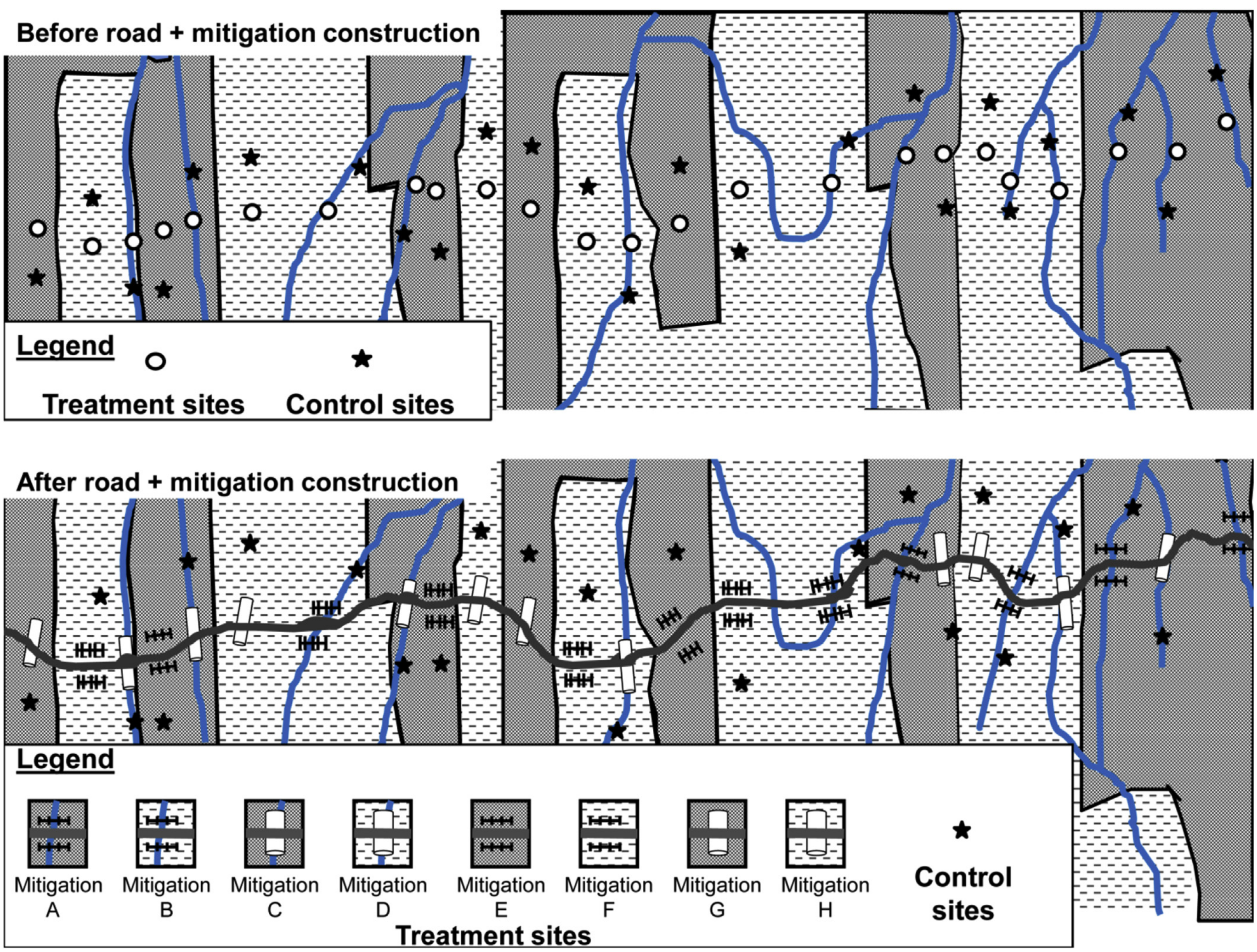

Fig. 13. BACI experimental design at the project development stage for Question 7: Where should we put crossing structures and barrier fencing? Specific questions: (1) Are mitigation structures placed at locations where streams intersect the proposed road (mitigation A - D) more effective at maintaining the population size of species X to levels similar to road-free areas compared to areas with similar mitigation but without streams (mitigation E–H)?, (2) Does mitigation effectiveness at stream vs. no stream locations depend on the type of mitigation structure installed (i.e., barrier fencing vs. culvert) and/or the cover type surrounding the mitigation structures (forest vs. crop fields)? In this example, the road and mitigation structures are constructed simultaneously. Data (e.g., relative population size) are collected at treatment and control sites before and after the road and mitigation structures are constructed. Here there are two different treatment types included (barrier fencing and culverts), each installed at two different locations (stream and no stream), each in two different cover types (forest and crop field). For each treatment, there are three replicates and all treatment sites are randomly located along the road segment while control sites are in road-free areas outside of the road effect zone.

intersect a proposed road should be more effective than in other locations without watercourses. Testing hypotheses about mitigation placement using a BACI experiment requires initiation at the project development stage (Fig. 13). This experiment will be very difficult to implement as it may be difficult for researchers to convince road planners to finance placement of structures in sites where one would *a priori* predict low mitigation effectiveness.

6. Challenges with experimentation

Using experimentation to evaluate road mitigation effectiveness does not come without challenges. First, ethical issues may arise when the experimental design includes mitigation measures that the researcher suspects (but has not yet demonstrated) to be ineffective. A possible solution to this issue might be to build all the structures to the design suspected to be effective, but install reversible modifications in some (randomly selected) that 'downgrade' them to designs that are assumed to be less effective. If it turns out that the researcher's 'gut feeling' was correct, the less effective structures can be readily upgraded (modifications removed) following the experiment. Second, for experiments that address questions requiring several years of data, researchers may need to design experiments such that road agencies do not need to wait several years for findings. For example, an experiment to determine the effectiveness of different types of crossing structures for improving connectivity for species X should be designed to provide useful information to road agencies within the first few years as well as population-level insights over the full duration of the experiment. Designing experiments in this way will help deliver useful information to managers and decisions makers both in the short term and long term of the study. Third, studies addressing questions that require large temporal scales, such as some of those addressed in this paper, are not compatible within most graduate programs (i.e., a single MSc or PhD thesis), post-doctorate fellowships, or short-term research contracts (van der Ree et al., 2011). As a consequence, researchers are often reluctant to carry them out or are unable to find stable funding for the required period. A fourth difficulty in planning mitigation experiments is that road planners may need to be convinced of the need for experimentation. For example, transportation agencies may not like the idea of installing some structures that are predicted to be less effective than others. The most feasible solution to this is for researchers to plan the range of structure types such that the expected 'worst' structure is still a design that is expected to be effective. The question then becomes, is it actually effective, or is another (e.g., taller, wider) design needed. Finally, many road agencies may even argue that this type of work is outside of their remit i.e., they are not research funding agencies. In summary, to help transportation agencies realize the potential gains in knowledge, performance, and cost saving, researchers must become more engaged with those setting policy for funding, planning, designing, building and maintaining the infrastructure (van der Ree et al., 2015b).

In situations where experimentation is not feasible, some information can still be derived from observational and modelling studies. For example, the use of global positioning system (GPS) and satellite-based telemetry to monitor wildlife movements (van Manen et al., 2001; Waller and Servheen, 2005) may be useful for addressing the question: Where should we place crossing structures and barrier fencing? Movement data can be collected from GPS-collared animals monitored before the construction of a new road, and virtual road crossing frequencies can be modelled as a function of cover type (e.g., forest, wetlands, streams, crop fields). This information can then be used to install mitigation structures in locations where animals are most likely to cross the future road. After the road and mitigation structures are constructed, monitoring of GPS-collared animal movements would continue to determine whether crossing locations change.

Modelling studies can be useful for making predictions about mitigation effectiveness, although only empirical studies can test these predictions. For example, van der Ree et al. (2009) used population viability modelling to predict the effectiveness of under-road tunnels installed to restore connectivity for the critically endangered Mountain Pygmy-possum in Australia (*Burramys parvus*; Mansergh and Scotts, 1989). They estimated that the tunnels reduce, but do not completely eliminate the negative effect of the road, with the density of the population affected by the mitigated road 15% lower than a comparable undivided population nearby (van der Ree et al., 2009). While population viability analyses (PVA) are typically strongly limited by lack of accurate population parameters (van der Ree et al., 2009), in the example above, the authors were fortunate to have a 20-year data set with which to parameterize their model. Spatially explicit population models can be used to predict optimal locations and types of mitigation structures, and the crossing rates that are likely to be required to achieve certain population-level outcomes (see van der Grift and Pouwels, 2006; Ascensão et al., 2013) but here, as elsewhere, strong tests of these hypotheses require comparison of modelled predictions with empirical data.

7. Concluding remarks

If road mitigation experiments became a standard part of any new or existing road project, how will the next 20–30 years look? Quite simply, improvements in road mitigation would increase rapidly. Each new mitigation experiment would build on the insights from past experiments (even those in other regions or on other species) and be incorporated in the design of new road mitigation experiments to ensure more effective mitigation. Currently there is simply not enough information on the effectiveness of mitigation measures to know, for example, the degree to which a bigger underpass is more or less effective at the population-level than a smaller underpass. If an experiment was designed to address this question, the next experiment could then compare that new standard with something even better, thus continually improving knowledge about mitigation effectiveness and increasing predictive power. If the information gained from experiments became a standard part of road upgrades, then fairly quickly road projects would improve ecological condition rather than worsen it. This might include the protection of road-less areas by preventing road construction (Selva et al., 2011), when it cannot be shown that road mitigation will be effective for all relevant species in the region.

It should be noted that compromise and trade-offs are inherent in the placement, design and construction of all road projects (Roberts and Sjolund, 2015). Multiple route options are evaluated during planning for their social, environmental and economic costs and benefits, and the final route and road-design is one where as many costs as possible are minimised; however it is inevitable that some specific impacts cannot be avoided. The same trade-offs and compromises are a part of experimentation. We are acutely aware that some of the study designs and recommendations outlined here are difficult to achieve (e.g., Figs. 7, 8 and 13) and while it would be ideal from an experimental or study design perspective to have them fully implemented, we realise that this may not always be possible. However, our thesis is that the science of road ecology will move forward significantly even if our recommendations are only partially implemented on the more logistically difficult designs, especially if adopted on numerous projects globally or fully implemented in a few studies (van der Ree et al., 2015b).

Furthermore, by taking the approach of coordinated distributed experiments (CDEs) to research and monitoring (e.g., Fraser et al., 2013), road agencies can significantly increase the quality of the study designs and boost sample sizes because they can more easily pool money for research across a number of projects and plan more comprehensive monitoring programmes that achieve superior outcomes. CDEs have been successfully used in other fields of ecology (Fraser et al., 2013). Standardized methods and controlled protocols allow for much stronger meta-analyses and hence insights into the effectiveness of road mitigation (van der Ree et al., 2015b).

In any case, for road agencies to make more informed and reliable decisions, we must modify our approach to evaluating the effectiveness of mitigation measures. Road mitigation experiments are the best systematic approach that can explicitly and more reliably reveal the effects of important design and landscape parameters (i.e., characteristics of the structure, road and traffic conditions, or adjacent landscape features) on mitigation effectiveness. By identifying and testing a theory, even simple theories or hypothesized relationships, the results of the experiments can be used to inform future mitigation. The research questions typically addressed about mitigation structures are not necessarily wrong, but with a little extra thought and resources, the same research could provide information relevant to different species, landscapes, roads and/or road projects (van der Ree et al., 2015b). These “laws” of road ecology will provide information that has relevance beyond the immediate question or problem. To do so, researchers need to not shy away from “riskier” research that requires high level collaborations despite the fact that road mitigation experiments may appear less “safe” for their research program (Houlahan, 1998). Experiments investigating mitigation effectiveness are a relevant and necessary way forward in road ecology, and this should be acknowledged by both the transportation agencies and research funding agencies.

Acknowledgements

This paper began through discussions at a meeting in Montreal, QC in 2009 and continued through a road ecology workshop held at Auberge Val Carroll, QC, Canada. We thank the staff of Val Carroll for hosting a wonderful weekend and L. Francisco Madriñan for comments in earlier discussions leading towards this paper.

Appendices A–E. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2015.01.048.

References

Ascensão, F., Clevenger, A., Santos-Reis, M., Urbano, P., Jackson, N., 2013. Wildlife–vehicle collision mitigation: is partial fencing the answer? An agent-based model approach. Ecol. Model 257, 36–43.
Benítez-López, A., Alkemade, R., Verweij, P.A., 2010. The impact of roads and other infrastructure on mammal and bird populations: a meta-analysis. Biol. Conserv. 143, 1307–1316.
Clevenger, A.P., Ford, A.T., 2010. Wildlife crossing structures, fencing, and other highway design considerations. In: Beckmann, J.P., Clevenger, A.P., Huijser, M.P., Hilty, J.A. (Eds.), Safe Passage: Highways, Wildlife, and Habitat Connectivity. Island Press, Washington, pp. 17–49.
Connolly-Newman, H.R., Huijser, M.P., Broberg, L., Nelson, C.R., Camel-Means, W., 2013. Effect of cover on small mammal movements through wildlife underpasses along US highway 93 north, Montana, USA. In: Proceedings of the 2013 International Conference on Ecology and Transportation, p. 12. Available: http://www.icoet.net/ICOET_2013/proceedings.asp (accessed 28.12.13.).
Cunnington, G.M., Garrah, E., Eberhardt, E., Fahrig, L., 2014. Culverts alone do not reduce road mortality in anurans. Ecoscience 21, 69–78.
Fahrig, L., Rytwinski, T., 2009. Effects of roads on animal abundance: an empirical review and synthesis. Ecol. Soc. 14, 21. Available: http://www.ecologyandsociety.org/vol14/iss1/art21/ (accessed 20.07.13.).
Fraser, L.H., Henry, H.A., Carlyle, C.N., White, S.R., Beierkuhnlein, C., Cahill Jr., J.H., Casper, B.B., Cleland, E., Collins, S.L., Dukes, J.S., Knapp, A.K., Lind, E., Long, R., Luo, Y., Reich, P.B., Smith, M.D., Sternberg, M., Turkington, R., 2013. Coordinated distributed experiments: an emerging tool for testing global hypotheses in ecology and environ mental science. Front. Ecol. Environ. 11, 147–155.
Glista, D.J., De Vault, T.L., DeWoody, J.A., 2009. A review of mitigation measures for reducing wildlife mortality on roadways. Landsc. Urban Plan. 91, 1–7.
Houlahan, J., 1998. Big problems, small science. Conserv. Ecol. 2 (1), R1. Available: http://www.consecol.org/vol2/iss1/resp1/ (accessed 01.05.14.).
Huijser, M.P., McGowen, P.T., 2010. Reducing wildlife-vehicle collisions. In: Beckmann, J.P., Clevenger, A.P., Huijser, M.P., Hilty, J.A. (Eds.), Safe Passage: Highways, Wildlife, and Habitat Connectivity. Island Press, Washington, pp. 51–74.
Lesbarrères, D., Fahrig, L., 2012. Measures to reduce population fragmentation by roads: what has worked and how do we know? Trends Ecol. Evol. 27, 374–380.
Mansergh, I.M., Scotts, D.J., 1989. Habitat continuity and social organisation of the mountain pygmy-possum restored by tunnel. J. Wildl. Manag. 53, 701–707.
McCall, S.C., McCarthy, M.A., van der Ree, R., Harper, M.J., Cesarini, S., et al., 2010. Evidence that a highway reduces apparent survival rates of squirrel gliders. Ecol. Soc. 15, 27. Available: http://www.ecologyandsociety.org/vol15/iss3/art27/ (accessed 21.08.13.).
Ontario Ministry of Transportation, 2010. Southern Highways Program 2010–2014. Ontario Ministry of Transportation, Highways Construction Programs. Available: http://www.mto.gov.on.ca/english/pubs/highway-construction/southern-highway-2010/highway-planning.shtml (accessed 25.09.13).
Roberts, K., Sjölund, A., 2015. Incorporating biodiversity issues into road design: the road agency perspective. In: van der Ree, R., Smith, D., Grilo, C. (Eds.), Handbook of Road Ecology. John Wiley & Sons, Oxford, pp. 27–31.
Roedenbeck, I.A., Fahrig, L., Findlay, C.S., Houlahan, J.E., Jaeger, J.A.G., et al., 2007. The Rauischholzhausen agenda for road ecology. Ecol. Soc. 12 (1), 11. Available: http://www.ecologyandsociety.org/vol12/iss1/art11/ (accessed 20.07.13).
Rytwinski, T., Fahrig, L., 2012. Do species life history traits explain population responses to roads? A meta-analysis. Biol. Conserv. 147, 87–98.
Selva, N., Kreft, S., Kati, V., Schluck, M., Jonsson, B.-G., Mihok, B., Okarma, H., Ibisch, P.L., 2011. Roadless and low-traffic areas as conservation targets in Europe. Environ. Manage 48, 865–877.
Soanes, K., Carmody Lobo, M., Vesk, P.A., McCarthy, M.A., Moore, J.L., et al., 2013. Movement re-established but not restored: inferring the effectiveness of road crossing mitigation for a gliding mammal by monitoring use. Biol. Conserv. 159, 434–441.
Spellerberg, I.F., 2002. Ecological Effects of Roads. Science Publisher, Plymouth, p. 251.
Trombulak, S.C., Frissell, C.A., 2000. Review of ecological effects of roads on terrestrial and aquatic communities. Conserv. Biol. 14 (1), 18–30.
U.S. Department of Transportation, 2012. Flexibility in Highway Design. U.S. Department of Transportation, Federal Highway Administration, Office of Planning, Environment, and Realty (HEP). Available: http://www.fhwa.dot.gov/environment/publications/flexibility/ (accessed 25.09.13).
van der Grift, E.A., Findlay, S., van der Ree, R., Fahrig, L., Houlahan, J., Jaeger, J.A.G., Klar, N., Madriñan, L.F., Olson, L., 2013. Evaluating the effectiveness of road mitigation measures. Biodivers. Conserv. 22 (2), 425–448.
van der Grift, E.A., Pouwels, R., 2006. Restoring habitat connectivity across transport corridors: identifying high-priority locations for de-fragmentation with the use of an expert-based model. In: Davenport, J., Davenport, J.L. (Eds.), The Ecology of Transportation: Managing Mobility for the Environment. Springer, Dordrecht, pp. 205–231.
van der Ree, R., 2006. Road upgrade in Victoria a filter to the movement of the endangered squirrel glider *Petaurus norfolcensis*: results of a pilot study. Ecol. Manag. Restor. 7, 226–228.
van der Ree, R., Bennett, A.F., 2003. Home range of the squirrel glider *Petaurus norfolcensis* in a network of linear habitats. J. Zool. 259, 327–336.
van der Ree, R., Bennett, A.F., Gilmore, D.C., 2003. Gap-crossing by gliding marsupials: thresholds for use of isolated woodland patches in an agricultural landscape. Biol. Conserv. 115, 241–249.
van der Ree, R., Cesarini, S., Sunnucks, P., Moore, J.L., Taylor, A.C., 2010. Large gaps in canopy reduce road crossing by a gliding mammal. Ecol. Soc. 15, 35. Available: http://www.ecologyandsociety.org/vol15/iss34/art35/ (accessed 29.09.13).
van der Ree, R., Smith, D., Grilo, C., 2015a. *Handbook of Road Ecology*. John Wiley & Sons; Oxford, p. 552.
van der Ree, R., Heinze, D., McCarthy, M., Mansergh, I., 2009. Wildlife tunnel enhances population viability. Ecol. Soc. 14 (2), 7. Available: http://www.ecologyandsociety.org/vol14/iss2/art7/ (accessed 29.09.13).
van der Ree, R., Jaeger, J.A.G., Rytwinski, T., van der Grift, E., 2015b. Good science and experimentation are needed in road ecology. In: van der Ree, R., Smith, D., Grilo, C. (Eds.), Handbook of Road Ecology. John Wiley & Sons; Oxford, pp. 71–81.
van der Ree, R., Jaeger, J.A.G., van der Grift, E.A., Clevenger, A.P., 2011. Effects of roads and traffic on wildlife populations and landscape function: road ecology is moving towards larger scales. Ecol. Soc. 16 (1), 48. Available: http://www.ecologyandsociety.org/vol16/iss1/art48/ (accessed 29.09.13).
van der Ree, R., van der Grift, E., 2015. Recreational co-use of wildlife crossing structures. In: van der Ree, R., Smith, D., Grilo, C. (Eds.), Handbook of Road Ecology. John Wiley & Sons; Oxford, pp. 184–189.
van der Ree, R., van der Grift, E.A., Gulle, N., Holland, K., Mata, C., et al., 2007.

Overcoming the barrier effect of roads: how effective are mitigation strategies? An international review of the use and effectiveness of underpasses and overpasses designed to increase the permeability of roads for wildlife. In: Irwin, C.L., Nelson, D., McDermott, K.P. (Eds.), Proceedings of the 2007 International Conference on Ecology and Transportation. Center for Transportation and the Environment, North Carolina State University, Raleigh, pp. 423–431.

van Manen, F.T., Jones, M.D., Kindall, J.L., Scheick, B.K., 2001. Determining the potential mitigation effects of wildlife passageways on black bears. In: Irwin, C.L., Garrett, P., McDermott, K.P. (Eds.), Proceedings of the 2001 International Conference on Ecology and Transportation. Center for Transportation and the Environment, North Carolina State University, Raleigh, pp. 435–446.

Waller, J.S., Servheen, C., 2005. Effects of transportation infrastructure on grizzly bears in northwestern Montana. J. Wildl. Manag. 69 (3), 985–1000.