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REVIEW

Do wildlife crossing structures mitigate the barrier effect of roads on animal movement? A global assessment

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Abstract

1. The widespread impacts of roads on animal movement have led to the search for innovative mitigation tools. Wildlife crossing structures (tunnels or bridges) are a common approach; however, their effectiveness remains unclear beyond isolated case studies.
2. We conduct an extensive literature review and synthesis to address the question: What is the evidence that wildlife crossing structures mitigate the barrier effect of roads on wildlife movement? In particular, we investigated whether wildlife crossing structures prevented an expected decline in cross-road movement, restored movement to pre-construction conditions, or improved movement relative to taking no action.
3. In an analysis of 313 studies, only 14% evaluated whether wildlife crossing structures resulted in a change in animal movement across roads. We identified critical problems in existing studies, especially the lack of benchmarks (e.g. pre-road, pre-mitigation, or control data) and the use of biased comparisons.
4. Wildlife crossing structures allowed cross-road movement in 98% of data sets and improved movement in ~60%. In contrast, the decline of wildlife movement was prevented in fewer than 40% of cases. For most structure types and species groups there was insufficient evidence to draw generalisable conclusions.
5. *Synthesis and Applications*: The evidence to date suggests that wildlife crossing structures *can* mitigate the barrier effect of roads on wildlife movement, but in many cases have been poorly implemented or evaluated. The most supported measures were the addition of ledges and vegetation cover to increase movement

for small mammals; underpasses to prevent the decline in movement of ungulates following road construction; and improving road-crossing for arboreal mammals using canopy bridges and vegetated medians. We strongly recommend that future use of crossing structures closely adheres to species-specific, best-practice guidelines to improve implementation and be paired with a thorough evaluation that includes benchmark comparisons, particularly for measures and species that lack sufficient evidence (e.g. invertebrates, amphibians, reptiles, birds, and overpasses).

KEYWORDS
connectivity, conservation evidence, fragmentation, mitigation, overpass, road ecology, underpass

1 | INTRODUCTION

Roads and traffic place increasing pressure on the natural environment, particularly on wildlife (e.g. Ascensão et al., 2018; Bennett, 2017; Collinson et al., 2019; Grilo et al., 2021). One impact is the 'barrier effect', whereby animal movement across roads is reduced, likely reducing population persistence (Bennett, 2017; Jaeger et al., 2005; van der Ree et al., 2009). When a road impedes daily movements, resources that occur on the opposite side of the road are less accessible (Eigenbrod et al., 2008; Liu et al., 2017; Singer, 1978). Roads may filter the movement of individuals based on age or sex, and thus disrupt population demographics such as sex ratios and age structure (Cibot et al., 2015; Mansergh & Scotts, 1989; Sawaya et al., 2019). Barriers to movement can also impact seasonal migration and dispersal (Seidler et al., 2015), and reduce the capacity to (re-)colonise vacant patches (Barbosa et al., 2020). In some cases, populations separated by a road can become genetically isolated, where inbreeding and genetic drift result in a loss of genetic variation (Gerlach & Musolf, 2000; Holderegger & Di Giulio, 2010; Keller & Largiadèr, 2003). Measures that promote animal movement across roads have therefore received much attention in recent decades.

Efforts to mitigate the barrier effects of roads on wildlife movement have led to innovative solutions (Lesbarrères & Fahrig, 2012). Wildlife crossing structures—bridges (overpasses) or tunnels (underpasses) that allow wildlife to safely cross roads, railways, or utility lines—are perhaps best known. These structures have been built for a range of species, including for the critically endangered Florida panther in the United States (Foster & Humphrey, 1995), Christmas Island red-crabs (Muller & Misso, 2015), and lemurs in Madagascar (Mass et al., 2011). Less-common measures include road closures, cross-walks, traffic calming, wildlife detection systems, and fence removal (van der Ree et al., 2007). Thousands of wildlife crossing structures have been implemented worldwide, with larger structures often costing millions of dollars (Huijser et al., 2009). Such measures will likely become even more prevalent, as they are often a condition of approval for new road projects (Laurance et al., 2014; Meijer et al., 2018). Given the rising popularity, financial cost, and assumed effectiveness of these structures, it is important to determine whether they reduce the barrier effect of roads on wildlife movement.

Several narrative reviews have summarised the literature on the success of mitigation measures at promoting wildlife movement (Bennett, 2017; Corlatti et al., 2009; Lesbarrères & Fahrig, 2012; van der Ree et al., 2007). More recently, a meta-analysis explored the factors that influence acceptance and use of crossing structures by wildlife (Denneboom et al., 2021). However, there has been no attempt to quantitatively synthesise the evidence that crossing structures *affect* wildlife movement. For example, did the structure (a) prevent an expected decline in cross-road movement?, (b) restore movement to pre-construction conditions?, or (c) improve movement relative to taking no action? These inferences require comparison to a benchmark against which success can be evaluated, including 'natural' non-road conditions, pre-barrier conditions, or unmitigated road conditions. Building a general understanding requires synthesising across multiple studies, taxa, and mitigation types, and considering the local context, mitigation goals, and the strength of the study design. Such a synthesis is needed and timely.

Here, we conduct an extensive literature review to ask: What is the evidence that wildlife crossing structures mitigate the barrier effect of roads on wildlife movement? We searched peer-reviewed articles and grey literature for evaluations of wildlife crossing structures. We identified the potential of each evaluation to make inferences about a change in movement facilitated by a wildlife crossing structure(s). We summarise the current state of knowledge across 10 species groups and present a quantitative synthesis of the findings. In doing so, we also identify systemic problems in the literature that limit our ability to confirm that road barrier mitigation maintains or increases cross-road movement of wildlife.

2 | MATERIALS AND METHODS

2.1 | Search methods

We used two search strategies to maximise comprehensiveness and obtain as many relevant documents as possible. First, we conducted a systematic search of the academic databases ISI Web of Science

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(WoS), Scopus, and ProQuest Science, Technology and Medicine. We used the following search string (in WoS format):

Roads terms: (road* OR highway* OR traffic)
AND
Wildlife terms: (wildlife OR fauna OR animal* OR amphibian* OR reptile* OR mammal* OR ungulate* OR bird* OR invertebrate* OR insect* OR butterfl*)
AND
Mitigation terms: (culvert* OR tunnel* OR passage* OR overpass* OR underpass* OR bridge* OR pole* OR fenc* OR crossing structure* OR mitigation).

A document must have included at least one road term, one wildlife term, and one mitigation term in the title, abstract, or keywords to be returned by our search (e.g. 'road' and 'wildlife' and 'crossing structure').

Second, we used a purposive search to supplement our systematic search and capture research published in the grey literature, languages other than English, or information that might otherwise be overlooked by a systematic approach (e.g. literature that focused on a single species and did not use a general wildlife term in the title, abstract, or keywords). This included searching Google Scholar, thesis repositories, road ecology conference proceedings, textbooks, the websites of road ecology research institutes and specialist conservation or statutory organisations (e.g. Departments of Transport), as well as the reference sections of review papers and books (see Supporting Information). We also solicited suggested documents from international experts. The search was 'purposive' in that we purposefully sought documents that tested for an effect of mitigation measures on wildlife movement across roads. As such, the results of this search do not represent a comprehensive list of studies from the grey literature that simply monitor the use of a road mitigation by wildlife without comparison to a benchmark. We included documents up to the end of 2021. Ethics approval was not required for this project.

2.2 | Identifying studies of cross-road movement

We screened all documents to identify those describing wildlife movement in response to a mitigation measure, first by title and abstract, and then by reading full text (see Supporting Information for further details). The measures of cross-road movement included counts or rates of wildlife crossing as measured by tracks or cameras, as well as measures of the number, or proportion, of individuals that crossed, as measured by radio-telemetry, mark–recapture, or individual-based genetic techniques. We could only assess documents for which the full text was available, either online or through author-provided copies, in English, German, French, Dutch, Portuguese or Spanish, or if the authors translated the relevant information for us. We excluded aquatic organisms because the response to roads and wildlife crossing structures is notably different (e.g. a culvert may be a mitigation for terrestrial wildlife, but a barrier for aquatic species). All documents that met the criteria were read in full for further analysis. More than 90% of the documents described wildlife crossing structures and roads; therefore, we focused our analysis on those components, excluding studies on other mitigation or infrastructure types.

In some cases, a single document contained multiple investigations (e.g. chapters in a report or thesis). In others, a single investigation was described in multiple documents (e.g. the findings of a report later published as a peer-reviewed journal article, annual update reports of the same monitoring project, or data from a single road project re-analysed in multiple journal articles). To ensure that all relevant investigations were captured and to minimise the risk of pseudo-replication, we separated or condensed documents as necessary to identify 'studies,' each representing a unique evaluation of cross-road movement by wildlife at a mitigation measure(s). We use the term 'document' for an individual publication (e.g. journal article, thesis, report) and 'study' for a specific investigation within a document (i.e. the application of a study design to a research question). Finally, we use 'data set' for separate outcomes for each of multiple species or types of crossing structure within a study (see worked example in Supporting Information).

2.3 | Extracting information from studies

For each study, we extracted the location (e.g. road name, country), timing and duration of the study, number and type of mitigation measures monitored, study design used (after-only, control–impact, before–after, or before–after–control–impact) and species groups monitored (see Supporting Information for further details).

We classified the 'evaluation type' of each study based on the possible inferences that could be made about the effect of crossing structures on cross-road movement by wildlife. Evaluation types were based on the context of the construction project (new road, road upgraded (usually widened), mitigation retrofit to an existing road, or mitigation modification) and the type(s) of benchmark comparators used (no road, unmitigated road or unmitigated crossing structure, or no benchmark used), and reflected four common scenarios in wildlife crossing structure research (Figure 1): did the wildlife crossing structures

1. *Prevent a decline* in movement?
2. *Restore* movement to preconstruction levels?
3. *Improve* movement relative to leaving the road unmitigated?, or
4. *Allow* movement?

By considering each study in light of the evaluation type, it ensured our assessments of the outcome took into account the local context and goals of mitigation, which allowed us to make relevant inferences about mitigation success. For example, a finding of 'no change in movement' may be considered unsuccessful where the goal of mitigation was to improve wildlife movement across a road

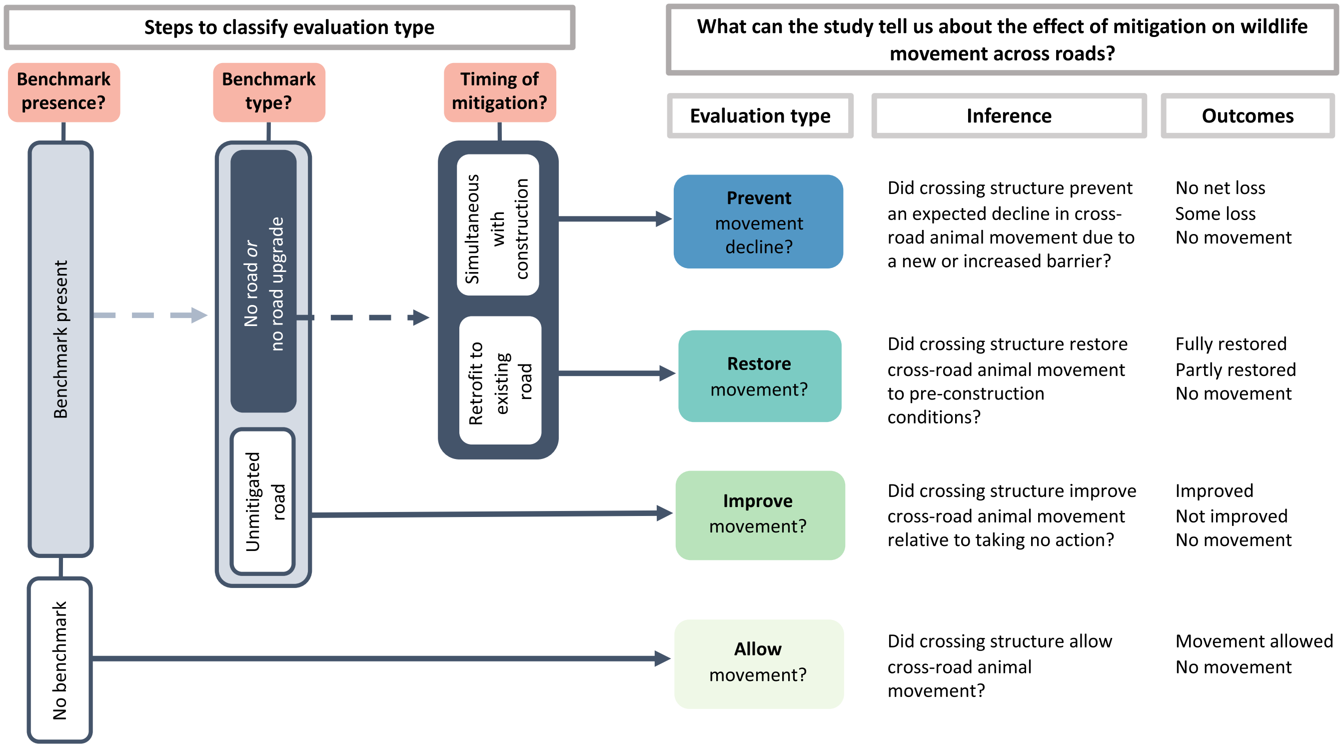

FIGURE 1 Overview of the four evaluation types and how they were categorised.

relative to an unmitigated site, yet the same finding would be a success where the goal of mitigation was to prevent a decline in movement after a road widening project (see Section 2.4 below).

2.3.1 | Biases in the benchmark

We identified two sources of bias in the benchmarks that inhibited the ability of a study to evaluate effectiveness (Figure 2). The first occurred in control–impact studies when mitigation measures were preferentially placed at sites thought to have high animal movement, leaving sites with lower animal movement as the control sites. In these cases, crossing structures purposefully intersect wildlife movement paths to maximise wildlife use. However, if the control sites are not placed at comparable locations, effectiveness cannot be determined, as the impact sites are predisposed to have higher movement than the control sites. Such studies would show that mitigation apparently improves cross-road movement even if no improvement has actually occurred. Note that this bias does not affect studies that include before data, that is, before–after and before–after–control–impact studies (Figure 2a).

The second bias occurred in studies where the effective sampling distance was longer at the mitigation sites than at the benchmark (Figure 2b). For example, before construction, a study may measure animal movement across a road over two 5-m wide track stations, one placed at the future site of an underpass (the impact site) and one placed at a site that will remain unmitigated as a control. The underpass is then installed, along with 50 m of funnel fencing in each direction. After construction and mitigation, if animal movement is measured using the same 5-m track station at each site, the sampling effort at the mitigation site has effectively increased, as it could capture all of the movements that would have occurred across the road within the entire 100-m fenced section (Figure 2b). The same effect does not occur at the unmitigated control site, creating a bias: the effective sampling distance at the mitigated site after mitigation is 95 m longer than at the control site (unless a correction factor is applied). This source of bias also occurs in studies that evaluate the effect of adding fences to wildlife crossing structures (i.e. 'modification' studies). While these studies can detect whether movement through a wildlife crossing structure changed after construction or fence modification, they cannot determine whether there has been an overall change in cross-road movement (McCollister & van Manen, 2010). Note studies that used individual-based animal tracking (e.g. radiotelemetry) were not susceptible to this issue because all road crossing by tagged individuals during the before condition would be detected, not just crossings at the future site of the crossing structure.

We examined each study for these two sources of bias, the first based on the stated rationale for the selection of the mitigation and control sites, and the second by comparing the effective length of road surveyed under mitigated and benchmark conditions. Studies that had either of these biases were re-classified as 'allow movement' evaluation types (i.e. effectively no benchmark). This is because the bias inherent in the study design means they cannot provide reliable information about a change in movement.

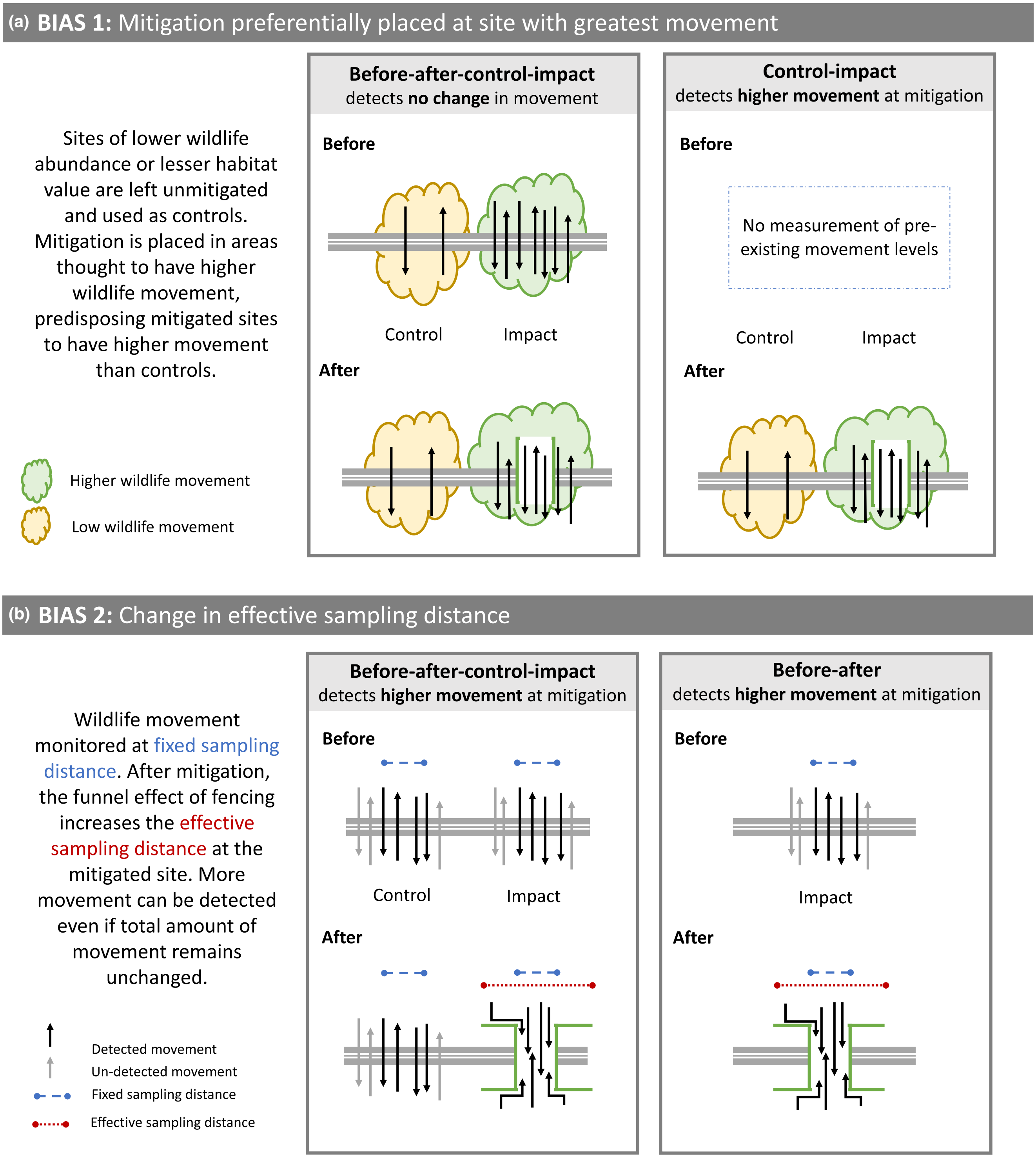

FIGURE 2 Illustration of sources of bias that can cause a study to mistakenly conclude that crossing structures have led to an increase in wildlife movement across the road barrier: (a) where mitigation is preferentially placed at sites with greater movement, and (b) where there is a change in the effective sampling distance at the mitigated site after mitigation.

2.4 | Qualitative tally of study outcomes

Given that our search was deliberately broad and not restrictive, some studies presented only semiquantitative or narrative results. While such studies would ordinarily be excluded from strictly quantitative approaches, such as a meta-analysis, we opted to consider inferences from a broader evidence base. For the qualitative assessment, we included all studies that presented information on cross-road movement by wildlife at a crossing structure and identified the responses to the level of species groups. Outcomes were assessed by comparing the amount of movement at the wildlife crossing structure to the amount of movement at the benchmark, except for studies in the *allow* category (no benchmark), where outcomes were simply 'movement' or 'no movement' (Figure 1). This was a simple qualitative assessment, irrespective of magnitude or statistical significance (worked examples provided in Supporting Information). We used the measures of wildlife movement provided by the authors (e.g. mean number of crossings, proportion of individuals crossing), using the raw data wherever possible. Where data were semiquantitative or narrative, we classified the outcome based on the author's description or we estimated it from figures. For each species group, we tallied the outcomes under each evaluation type (e.g. the number of times an evaluation showed no net loss, some net loss, etc.). Multiple outcomes were possible within a single species group where two species from the same group showed different responses (e.g. white-tailed deer used an underpass while moose did not, resulting in two outcomes for 'ungulates').

2.5 | Quantitative assessment of change in movement

The original intent of this paper was to conduct a meta-analysis; however, too few studies met the criteria. Instead, we compiled the available quantitative evidence of a change in wildlife movement due to wildlife crossing structures. For this assessment, we limited our scope to studies that (a) included a benchmark, allowing evaluation of a change in movement, and (b) presented quantitative data on cross-road movement, allowing the extent of the change to be determined. We calculated the percentage change in wildlife movement at the crossing structure relative to the benchmark:

$$\frac{(\text{crossings at mitigation}) - (\text{crossings at benchmark})}{\text{crossings at benchmark}} * 100\,\%$$

When there was movement at a wildlife crossing structure but not at the benchmark (i.e. crossings at benchmark = 0), we categorised these study outcomes as 'New movement' because a percent change in movement cannot be computed when movement at the benchmark equals zero. Similarly, when there was no movement at a wildlife crossing structure, we categorised these outcomes as evidence of 'No movement', rather than 100% decline.

3 | RESULTS

3.1 | Summary of literature search

Our search yielded 2688 documents published from 1935 to 2021. Four hundred and twenty-eight documents met our inclusion criteria. These were consolidated into 357 unique studies. Of these, 313 were of wildlife crossing structures at roads suitable for further analysis (Figure 3).

Only 19 studies assessed whether wildlife crossing structures *prevented* a decline in cross-road movement following construction, two assessed whether movement was *restored* compared to pre-construction levels, while 24 assessed whether wildlife crossing structures *improved* movement relative to an unmitigated road (Figure 3). Most commonly, studies evaluated whether wildlife crossing structures *allowed* cross-road movement by wildlife, with no comparison to a benchmark. These were after-only studies, that is, documenting movement through a crossing structure after its installation (258 studies), and those that contained biased benchmark comparisons (Figure 2; 10 studies).

The wildlife crossing structures included purpose-built passages for wildlife, with and without associated wildlife fencing; drainage structures; vegetated medians or natural canopy connectivity; and modifications applied to crossing structures, such as the addition of ledges, refuges, or other wildlife-friendly enhancements.

The studies were from 34 countries, predominantly the United States (117 studies), followed by Australia (50), Canada (34), the Netherlands (12) and Germany (11). The remainder were from elsewhere in Europe (55 studies from 16 countries), Asia (18 studies from 7 countries), South and Central America (11 studies from 3 countries), Africa (4 studies from 3 countries), and a global assessment (1 study).

Overwhelmingly, studies adopted an after-only approach, monitoring the use of crossing structures by wildlife with no benchmark comparison (Figure 4a). Mammals were the most evaluated taxon (269 studies), followed by reptiles (68), amphibians (57), and birds (55), with just 15 studies reporting invertebrates (Figure 4b). More than 70% of studies monitored more than one wildlife crossing structure, with 30% of studies monitoring 10 structures or more (Figure 4c). Monitoring duration was typically short, with 58% of studies lasting 2 years or less (Figure 4d).

3.2 | Do crossing structures reduce the barrier effect of roads on wildlife movement?

3.2.1 | Qualitative assessment

Our qualitative assessment resulted in 799 data sets (number of studies * number of responses reported per species group per study, Figure 5). Of the 25 *prevent movement decline* data sets, there was no net loss of animal movement in 36% of cases (6 data sets for ungulates, 2 data sets for medium–large carnivores, 1 for small mammals). The two *restore movement* data sets showed only partial restoration of movement for arboreal mammals. Of the 37 *improve movement* data sets, 62% showed improved movement relative to no mitigation, most commonly in small mammals (8 data sets) and arboreal mammals (5 data sets). Of the 735 data sets in the *allow movement* category, 729 showed use of crossing structures by wildlife, with all species groups represented.

3.2.2 | Quantifying change in movement

We extracted 79 data sets from 35 studies that quantified wildlife movement at crossing structures in comparison to a benchmark.

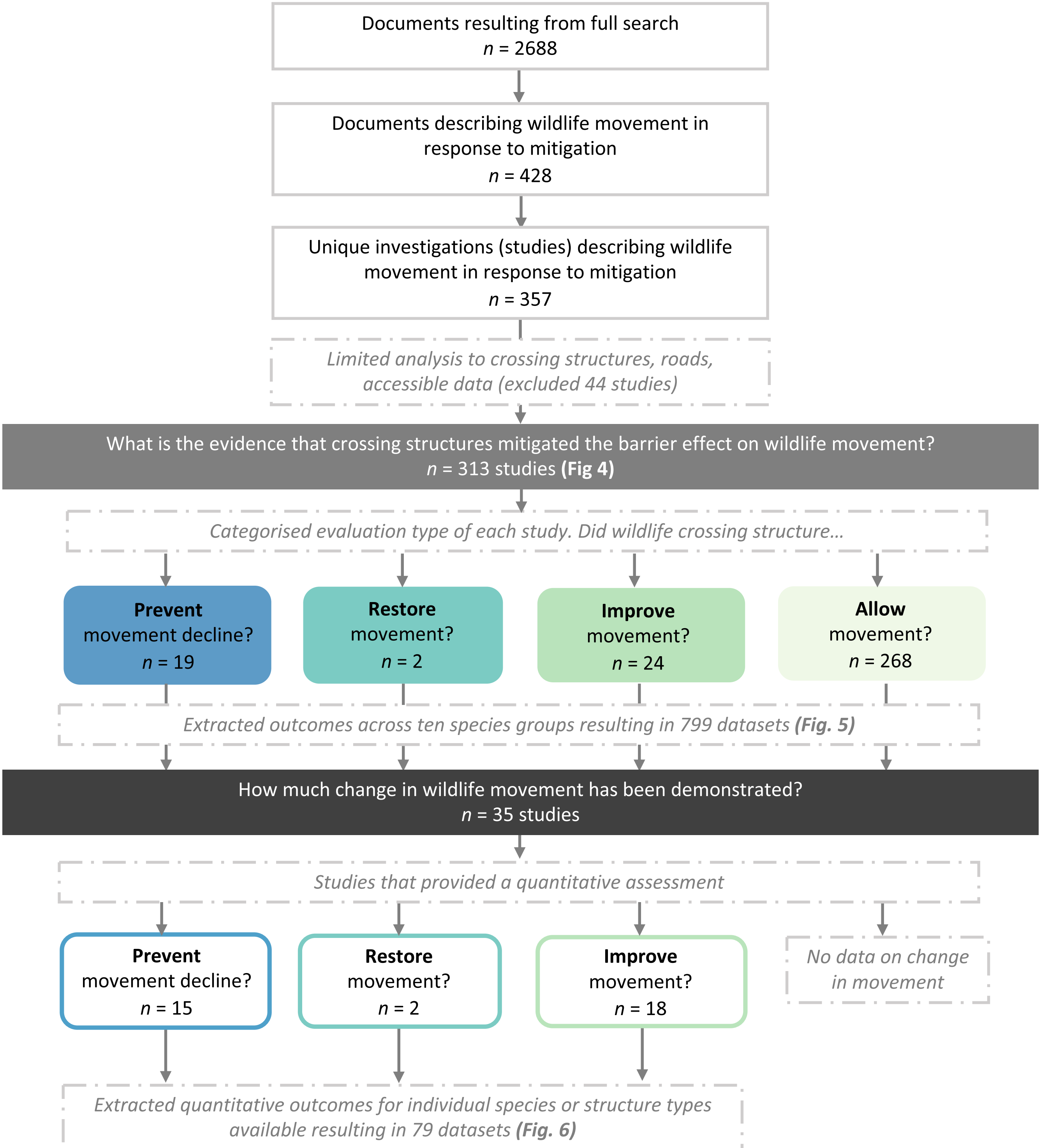

FIGURE 3 Results of literature search and screening, showing the progression of analysis from documents describing road barrier mitigation measures for wildlife movement, to unique studies evaluating wildlife crossing structures in each of the four evaluation types.

Only 22 data sets across five taxa and five structure types were from *prevent movement decline* evaluations (Figure 6a). Most of these showed a loss of movement, with declines ranging from 18% to 97%. In four instances, there was total loss of movement after construction despite the wildlife crossing structure. No net loss was achieved in nine *prevent movement decline* data sets, all for underpasses, with most of these for ungulates. The two *restore movement* data sets found only partial restoration, with movement at wildlife crossing structures 85% and 91% lower than non-road control sites (Figure 6b). Most data sets were from *improve movement* evaluations (55). Of these, most evaluated the effect of a modification to an existing structure relative to unmodified structures (38 data sets),

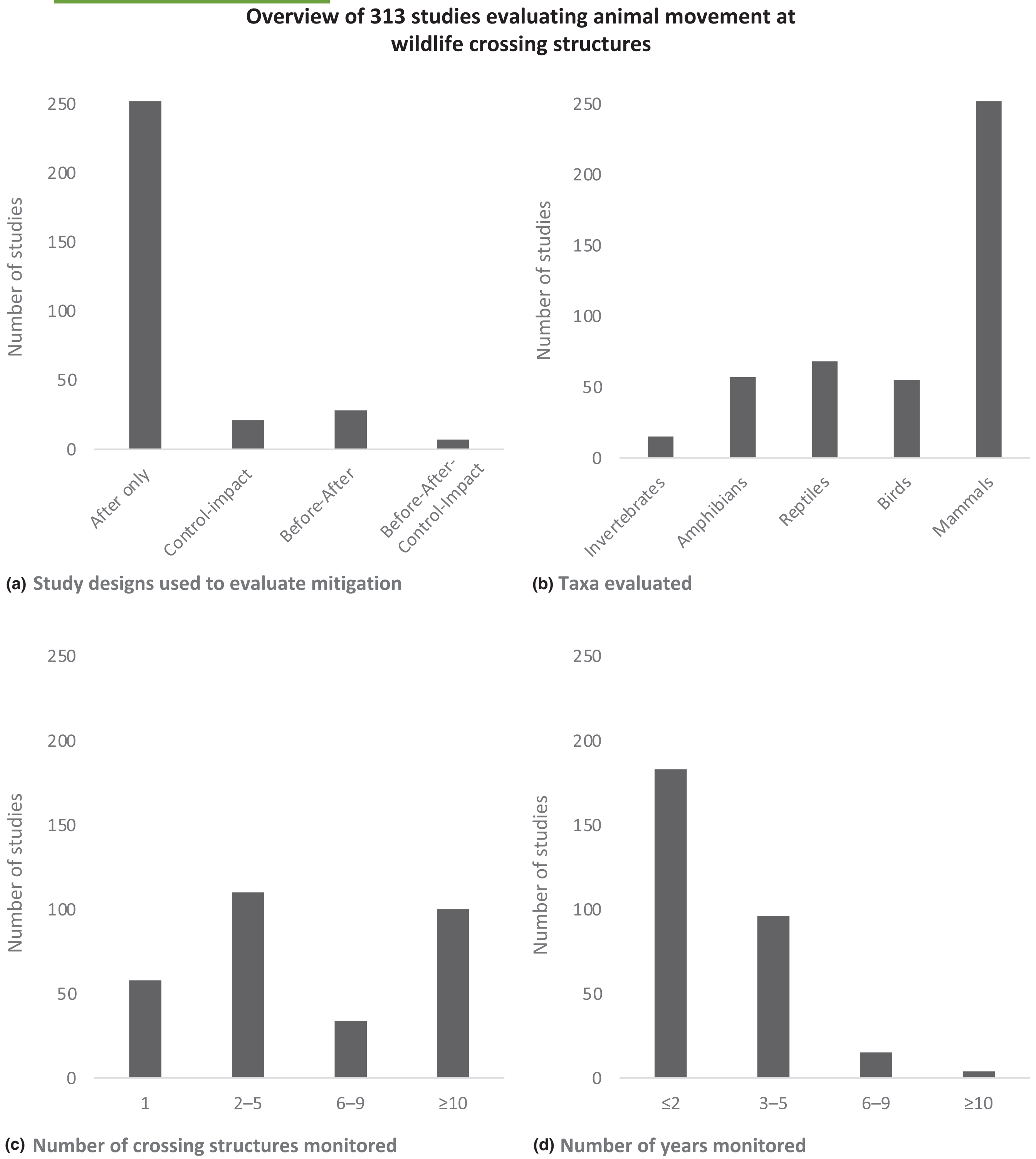

FIGURE 4 Summary of 313 studies evaluating the effect of wildlife crossing structures on wildlife movement, including (a) the study designs, (b) broad taxonomic groupings of species monitored, (c) number of mitigation measures monitored, and (d) number of years of monitoring. Some studies reported on multiple species or multiple study designs and as such are counted in multiple categories.

while only 17 evaluated the impact of a crossing structure itself. The majority of the *improve movement* data sets showed an improvement in movement (Figure 6c,d). Mitigation types with the most evidence for success were adding ledges or vegetation cover to crossing structures for small mammals (18 of 25 data sets showing increases in movement), and the use of canopy bridges and vegetated medians for arboreal mammals (4 showing movement increases and 0 showing no improvement).

Species groups	Prevent movement decline			Restore movement			Improve movement			Allow movement	
	No net loss	Some loss	No movement	Fully restored	Partly restored	No movement	Improved	Not improved	No movement	Yes	No movement
Invertebrates (17)	0	2	1	-	-	-	2	1	0	11	0
Amphibians (59)	-	-	-	-	-	-	2	0	0	55	2
Reptiles (68)	-	-	-	-	-	-	1	0	0	67	0
Birds (55)	-	-	-	-	-	-	1	1	0	53	0
Small mammals (178)	1	2	1	-	-	-	8	2	2	162	0
Carnivores (med—large) (154)	2	2	0	-	-	-	1	1	1	146	1
Ungulates (132)	6	3	1	-	-	-	0	2	0	120	0
Other large mammals (18)	0	1	0	-	-	-	-	-	-	17	0
Arboreal mammals (90)	0	2	0	0	2	0	5	1	1	76	3
Bats (28)	0	1	0	-	-	-	3	2	0	22	0
Total	**9**	**13**	**3**	**0**	**2**	**0**	**23**	**10**	**4**	**729**	**6**

FIGURE 5 State of the evidence that wildlife crossing structures mitigate the barrier effect of roads on wildlife movement across four evaluation types (refer to Figure 1 for description), with 799 data sets across 10 species groups. Counts indicate the number of data sets supporting each outcome. Unshaded cells with hyphens indicate no data available. Values ≥5 shaded darker. The number of data sets available for each species group is shown in parenthesis.

4 | DISCUSSION

4.1 | What do we know about the effect of crossing structures on wildlife movement?

There is abundant evidence that wildlife crossing structures allow animal movement across roads and other linear infrastructure. In our qualitative assessment of 799 data sets, only 1.6% showed no animal movement at crossing structures. However, far less attention has been paid to determining whether wildlife crossing structures prevent the decline of movement after construction, restore movement to pre-construction levels, or even whether they are an improvement over taking no action at all. Only 14% of studies have addressed these questions. The most supported measures were the addition of ledges or vegetation cover to existing crossing structures to increase movement for small mammals, underpasses preventing the decline in movement for ungulates following road construction or upgrade, and canopy bridges and vegetated medians to improve cross-road movement by arboreal mammals. For all other types of crossing structures, there is not enough evidence to draw conclusions about conservation outcomes or cost-effectiveness, or to interrogate the factors influencing success or failure. Taxonomic biases towards mammals strongly limit the conclusions for other taxa. For example, while reptiles and amphibians are among the taxa most likely to be impacted by roads, they are among the least commonly evaluated (Bennett, 2017; Denneboom et al., 2021; Rytwinski et al., 2016; van der Ree et al., 2007). We therefore conclude that while animals clearly *use* wildlife crossing structures, there is insufficient information regarding the *effect* on animal movement across roads.

The little evidence that exists suggests that wildlife crossing structures can improve movement relative to no action, but have rarely achieved no net loss or full restoration of wildlife movement. Wildlife movement was higher when crossing structures were present than when they were absent (using either before data or control sites). When wildlife crossing structures did not improve movement, this was often because the road was not a barrier to begin with: that is, the animals crossed the road as often when wildlife crossing structures were absent as when they were present (e.g. open-adapted bats, Abbott et al., 2012; honeyeater birds, Pell & Jones, 2015; large, highly mobile butterflies, Zinner et al., 2018). In such cases, there is little need to mitigate the movement barrier and efforts to reduce mortality are likely more important (Ceia-Hasse et al., 2018; Jaeger et al., 2005). In contrast, most wildlife crossing structures evaluated to date have failed to prevent a decline in cross-road movement following road (re)construction. In many cases, wildlife movement declined despite purpose-designed crossing structures for the species, including elk (*Cervus canadensis*, Gagnon et al., 2015), moose (*Alces alces*, Olsson & Widen, 2008), bandicoots (*Isoodon macrourus* and

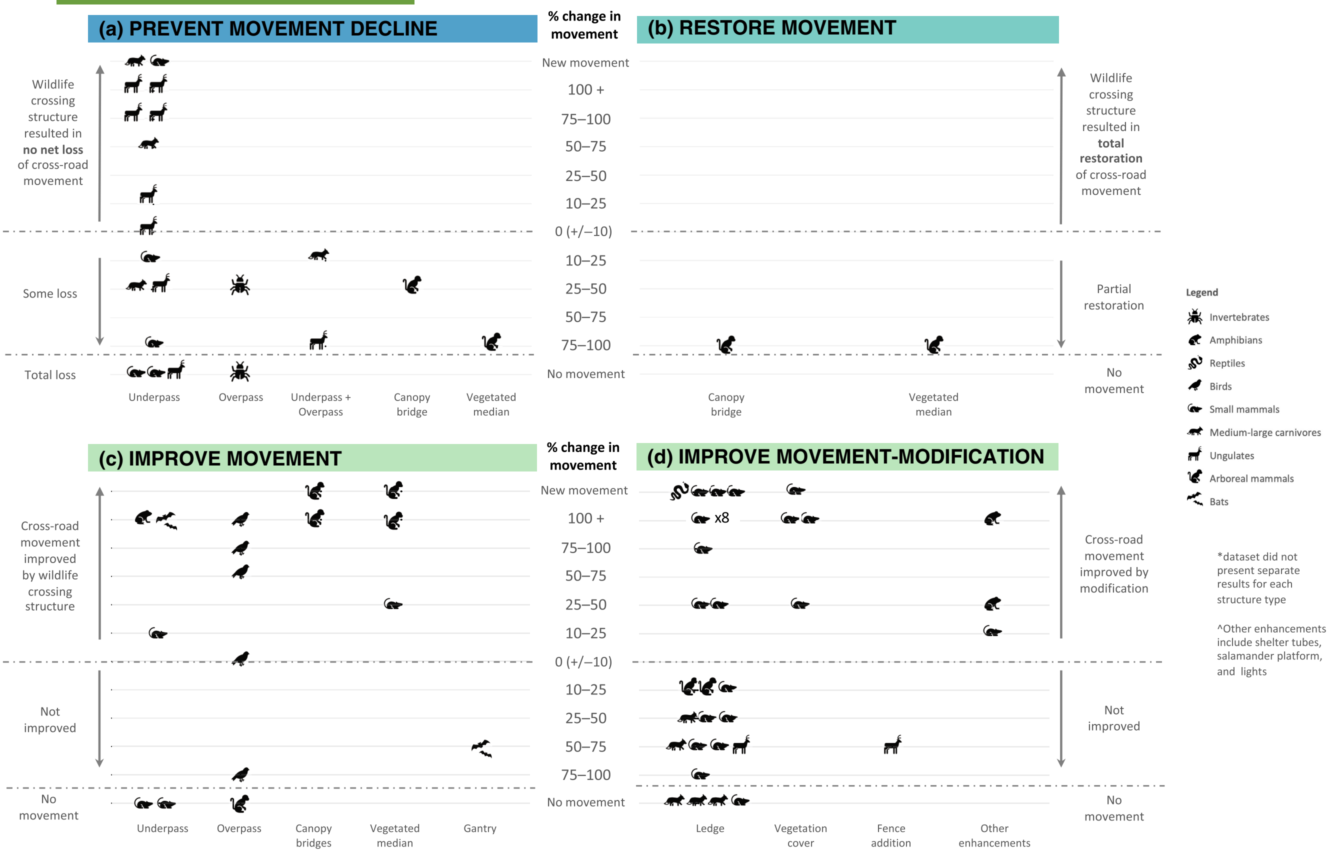

FIGURE 6 The percentage change in cross-road wildlife movement at crossing structures relative to a benchmark for each evaluation type (Figure 1): (a) prevent movement decline, (b) restore movement, (c) improve movment, and (d) improve movement studies that focused on modifications to existing structures. Each icon represents an individual data set reporting the response of a species to a crossing structure. No evaluations were available for the species group 'other large mammals'.

Perameles nasuta, Taylor & Goldingay, 2014) and American black bears (*Ursus americanus*, Van Manen et al., 2012). These examples are concerning, as they indicate that mitigation structures installed as part of the road construction approvals process were insufficient to mitigate the road barrier to wildlife movement.

Recognising that complete mitigation of road effects on movement may be impossible, van der Grift et al. (2013) proposed 'limited net loss' as a potential goal of wildlife crossing structures, whereby reduced movement is accepted provided that population persistence is not threatened. For example, Soanes et al. (2018) showed gene flow of a gliding mammal across a major highway was maintained despite lower-than-expected crossing rates. In other cases, the amount of movement may be considered insufficient, even if it is an improvement over unmitigated conditions. Hedrick et al. (2019) concluded that modifications to underpasses for salamanders were ineffective, despite an increase in crossings, as they served only a small percentage of the wider population. Thus, limited net loss targets must be underpinned by clear evidence that population persistence is maintained despite reduced levels of movement. Few studies have used population viability analysis to estimate the minimum required level of movement (e.g. Taylor & Goldingay, 2012), or combined data of crossing structure use with genetic or demographic data to evaluate population-level success (Ramalho et al., 2018; Sawaya et al., 2014; van der Ree et al., 2009). For example, while an amphibian tunnel allowed the movement of approximately 20%–40% of a marked population of common toads (*Bufo bufo*) across a road, it was insufficient as the population still experienced a 75% decline following installation (Ottburg & van der Grift, 2019). Therefore, while it is tempting to argue that 'some movement is better than none', this is clearly not the case if the population is extirpated, and represents an irresponsible approach to cost-effective conservation in the absence of supporting population-level data.

Importantly, the evidence to date does not suggest that wildlife crossing structures *cannot* mitigate the barrier effect of roads on wildlife movement, but rather that they have often been poorly implemented. Were wildlife crossing structures inherently flawed, we would not have expected to see them used by such a wide variety of species, to see consistent evidence of improved movement across roads, and even instances in which no net loss was achieved. While there may be conditions under which wildlife crossing structures can never fully mitigate road impacts on animal movement (e.g. certain road types, species, or structure designs), there is not yet evidence that this is the case. Still, our analysis supports a growing number of studies suggesting that current attempts to mitigate the barrier effects of roads are inadequate (e.g.

Bennett, 2017; Claireau et al., 2019) and there is an urgent need to improve the implementation of wildlife crossing structures. Proposed causes for lack of success include unsuitable vegetation on or surrounding a crossing structure (Georgii et al., 2011; Taylor & Goldingay, 2014); too few structures or structures located too far apart (e.g. Ottburg & van der Grift, 2019); unsuitable designs for target species or poor placement relative to animals' natural movement paths (e.g. Berthinussen & Altringham, 2012; Claireau et al., 2019); the need for habituation time (e.g. Soanes et al., 2013); and inadequate fencing (e.g. Van Manen et al., 2012). Other potentially important factors, such as road width and traffic volumes, are rarely investigated (Denneboom et al., 2021; Rytwinski et al., 2016). However, such reasons are typically speculative, as we lack a generalisable evidence base from which to improve future designs or identify thresholds beyond which the effect of a road cannot be mitigated.

4.2 | Towards better evaluations of road barrier mitigation

The most pressing and important way to improve the evidence base for wildlife crossing structures is to include appropriate benchmarks against which improvements can be measured and goals can be set. Such comparisons are the only way to demonstrate an *effect* of mitigation (Roedenbeck et al., 2007; Rytwinski et al., 2015; van der Grift et al., 2013). This is fundamental to improving the practice of road barrier mitigation for wildlife conservation. For example, >50% of data sets evaluating the capacity of wildlife crossing structures to prevent a decline in movement showed some loss of movement. Had these studies only monitored wildlife movement across the structure after construction, the mitigation may incorrectly have been considered a success and the loss of movement undetected. Benchmarks may include the use of control sites or before data, preferably both (Rytwinski et al., 2015), and these must be carefully selected to ensure they are appropriate and unbiased (Figure 2). Ideally, studies should aim to include multiple comparisons, enabling researchers to compare the performance of wildlife crossing structures against both unmitigated and 'no construction' conditions. Only three examples in our literature search took this approach (Gullé, 2006; Soanes et al., 2013; Zinner et al., 2018). Comparison benchmarks are notoriously difficult to include, particularly in studies constrained by construction timelines, or at the direction of organisations that do not prioritise data collected at sites or times not within the construction period (Lesbarrères & Fahrig, 2012; Rytwinski et al., 2015; van der Ree et al., 2015). However, road agencies, environmental regulators and land managers that strive to make evidence-based decisions must recognise that benchmarks are an essential component of evaluation, insist on their inclusion, and fund and support these investigations accordingly. Solutions to common challenges arising from different construction, landscape, and governance constraints have been discussed elsewhere (Lesbarrères & Fahrig, 2012; Rytwinski et al., 2015; van der Ree et al., 2015). Ultimately, where resources are limited, they should be spent on including benchmark comparators, rather than on further replication of after-only studies (Christie et al., 2019).

Appropriate benchmarks should avoid two important unintentional biases that limit the inference of studies. The first is when mitigation preferentially occurs at 'good' sites, while the remaining 'poor' sites are allocated as controls (Figure 2a). While it is sensible that expensive mitigation measures are placed near good wildlife habitat, known wildlife populations, or known movement paths, control sites must have these same qualities. Otherwise, they are predisposed to have lower cross-road movement, thus biasing a control–impact comparison. While collecting before data negates this risk, it is not always feasible. The random allocation of sites (e.g. Connolly-Newman et al., 2013), leaving some 'good' sites as unmitigated controls (e.g. Soanes et al., 2013), and measuring wildlife activity and habitat quality to ensure that controls and mitigated sites are comparable (e.g. Abbott et al., 2012) will ensure that control–impact studies enable robust evaluation of mitigation measures (Rytwinski et al., 2015).

The second bias involves changes in the effective sampling distance after mitigation (i.e. fence–funnel effects, Figure 2b). Studies most susceptible to this bias are before–after investigations that monitor wildlife movement at a fixed point (i.e. camera or track station). Two studies (Gagnon et al., 2015; Van Manen et al., 2012) clearly demonstrate the importance of avoiding this bias. In these studies, camera data showed large increases in cross-road movement after mitigation, suggesting that the crossing structure prevented a decline in movement, while corresponding telemetry data revealed an overall reduction in cross-road movement after mitigation. The contradiction occurs because the installation of fencing as part of the mitigation process funnels wildlife towards the crossing structure from a larger area, effectively increasing the length of road that is monitored when compared to before mitigation. This issue can be avoided by monitoring the same length of road before mitigation as the length of the fenced road after mitigation (or by making appropriate corrections), staging the installation of fencing, or by monitoring individual movements (e.g. using telemetry).

5 | CONCLUSIONS

Our review suggests that the evidence base for evaluating whether wildlife crossing structures mitigate the barrier effect of roads is extremely weak. After decades of building wildlife crossing structures, hundreds of published studies, and repeated calls for stronger evaluations (Roedenbeck et al., 2007; Rytwinski et al., 2015; van der Grift et al., 2013), most studies were not designed to demonstrate whether wildlife crossing structures prevented a barrier effect, restored movement to pre-construction conditions, or even improve movement relative to unmitigated roads. As road networks expand, reliable advice is needed for how (or if) road effects can be mitigated, and recommendations based on faulty evidence may do more harm than good. It is therefore imperative that we more critically appraise the performance of wildlife crossing structures. The large number of studies we found points to a clear appetite for evaluating the use of structures by wildlife, but this must be paired with robust methods that determine the return on investment for the conservation goal. Researchers, road agencies, and decision makers must prioritise studies that evaluate whether a mitigation measure actually mitigates a road effect rather than further demonstrating simple use of a wildlife crossing structure. At a minimum, such studies will require relevant, unbiased benchmarks if we are to develop a general understanding of effectiveness.

Our findings have important implications for managing the barrier effects of roads on wildlife movement. First, while the overall lack of data was limiting, several mitigation types had convincing evidence of effectiveness. Installing underpasses for ungulates, adding modifications to existing structures (such as ledges or vegetation cover) for small mammals, and installing canopy bridges and vegetated medians for arboreal mammals, all successfully reduced the negative impacts of roads on wildlife movement and managers should feel confident using these approaches. Second, the number of studies in which wildlife crossing structures failed to prevent a decline in cross-road movement is concerning, particularly where these structures were required as part of construction approvals. Regulators and environmental managers should be aware that no net loss and full restoration are not assured with the installation of wildlife crossing structures and have only been demonstrated in a handful of contexts. They therefore should ensure that future projects aspiring to achieve these goals: (1) closely adhere to species-specific, best-practice guidelines relating to the structure design, placement, number of structures installed within the project zone, and their management; and (2) be paired with thorough evaluations capable of assessing those goals. Third, researchers can use our findings to identify areas where further evidence is critical, namely evaluations of overpasses, and studies focusing on invertebrates, amphibians, reptiles, and birds.

AUTHOR CONTRIBUTIONS

Kylie Soanes, Trina Rytwinski, Lenore Fahrig, Marcel P. Huijser, Jochen A. G. Jaeger, Fernanda Z. Teixeira, Rodney van der Ree and Edgar A. van der Grift conceived the ideas and designed methodology; Kylie Soanes and Trina Rytwinski collected the data; Kylie Soanes analysed the data and led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

Data are available via FigShare https://doi.org/10.26188/24932892.v3 (Soanes et al., 2024).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Data S1. Supplementary Methods for Soanes et al., 2024.

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