BIOLOGY LETTERS

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Cite this article: Teixeira FZ, Rytwinski T, Fahrig L. 2020 Inference in road ecology research: what we know versus what we think we know. *Biol. Lett.* **16**: 20200140.
http://dx.doi.org/10.1098/rsbl.2020.0140

Received: 12 March 2020
Accepted: 30 June 2020

Subject Areas:
ecology, environmental science

Keywords:
road kill, road barrier, traffic disturbance, road mitigation, strong inference, stress response

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Electronic supplementary material is available online at https://doi.org/10.6084/m9.figshare.c.5050353.

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Conservation biology

Inference in road ecology research: what we know versus what we think we know

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Roads and traffic impacts on wildlife populations are well documented. Three major mechanisms can cause them: reduced connectivity, increased mortality and reduced habitat quality. Researchers commonly recommend mitigation based on the mechanism they deem responsible. We reviewed the 2012–2016 literature to evaluate authors' inferences, to determine whether they explicitly acknowledge all possible mechanisms that are consistent with their results. We found 327 negative responses of wildlife to roads, from 307 studies. While most (84%) of these responses were consistent with multiple mechanisms, 60% of authors invoked a single mechanism. This indicates that many authors are over-confident in their inferences, and that the literature does not allow estimation of the relative importance of the mechanisms. We found preferences in authors' discussion of mechanisms. When all three mechanisms were consistent with the response measured, authors were 2.4 and 2.9 times as likely to infer reduced habitat quality compared to reduced connectivity or increased mortality, respectively. When both reduced connectivity and increased mortality were consistent with the response measured, authors were 5.2 times as likely to infer reduced connectivity compared to increased mortality. Given these results, road ecologists and managers are likely over-recommending mitigation for improving habitat quality and connectivity, and under-recommending measures to reduce road-kill.

1. Introduction

Effects of roads and traffic on wildlife populations have been well-documented worldwide over the past two decades, across a wide range of terrestrial taxa [1–3]. Most effects are negative; populations are smaller, or species are absent, closer to roads and in landscapes with higher road densities. Amphibians and reptiles, wide-ranging large mammals with low reproductive rates and birds with large territories are most heavily impacted [3].

Road ecologists measure a huge array of animal responses to roads, including changes in population abundance, genetics, movement and reproduction (e.g. [4–6]). It is then very natural that researchers recommend mitigation measures based on their results in the Discussions of their papers [7]. These recommended measures generally fall into one of three major categories: measures intended to increase animal movement across roads, measures to reduce road-kill and measures to reduce traffic effects on roadside populations, such as pollution and traffic disturbances [8].

The mitigation measure(s) suggested by authors in their Discussions reflect their interpretations of the major mechanism underlying the impact of roads and traffic on population persistence of the species of interest [7]. These mechanisms fall into three categories, corresponding to the major mitigation categories (figure 1). First, roads may reduce connectivity (*sensu* [9]), limiting immigration and access to resources, thus reducing population size. Second, road-kill can reduce population size by increasing the mortality rate. Finally,

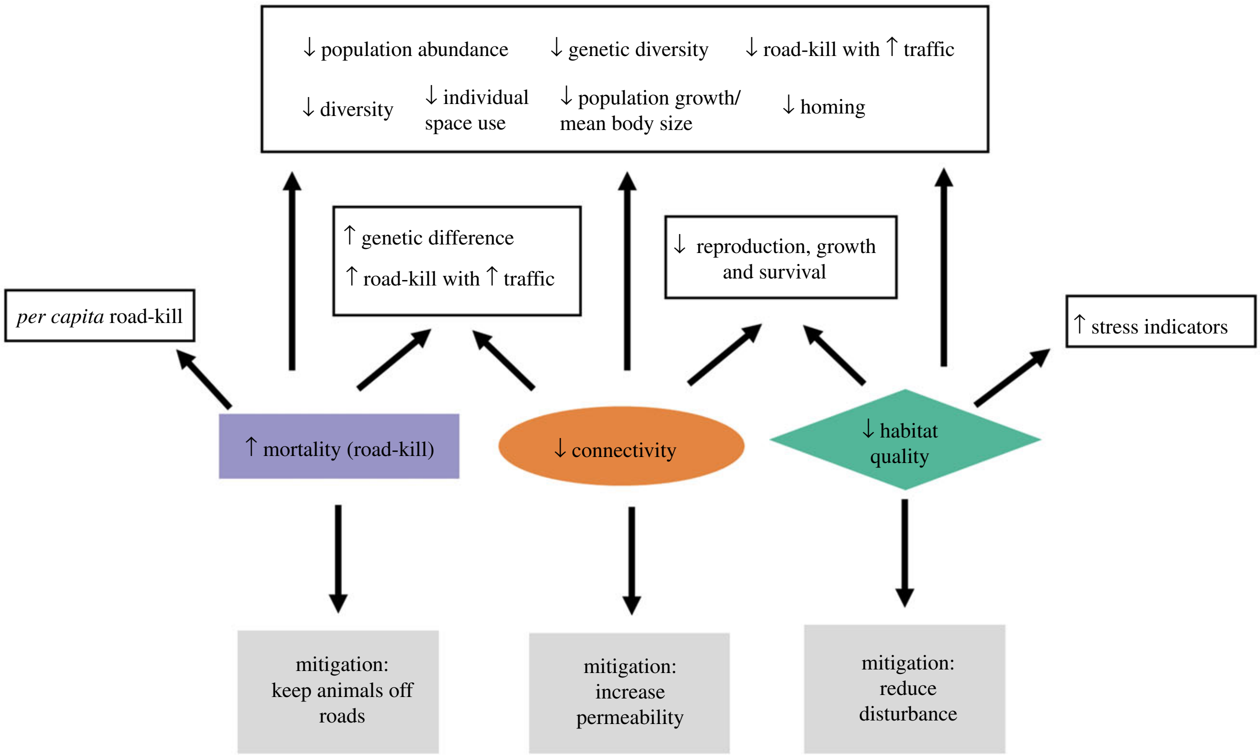

Figure 1. Measured animal responses to roads and traffic (white boxes) logically consistent with one, two or the three major mechanisms linking roads to decreased population persistence: increased mortality, reduced connectivity and reduced habitat quality.

traffic can reduce habitat quality in various ways, e.g. by pollution or traffic noise, leading to reduced reproductive rates and, again, smaller populations [8].

The effectiveness of a measure in recovering a population depends on whether it mitigates the main cause of road effects on population persistence in the particular situation. If the most important mechanism is reduced connectivity, then mitigation should emphasize structures that increase road permeability to movement, such as overpasses or tunnels [10,11]. If increased mortality through road-kill is the dominant cause of impacts on the population, then mitigation should aim to keep the animals off the road(s), e.g. through road walls or wildlife fencing [12,13]. Finally, if the impacts of roads and traffic are caused largely by disturbances that reduce habitat quality, then mitigation should aim to reduce these disturbances, e.g. by engineering solutions to reduce noise and chemical pollutants [14,15].

Observing that roads reduce the abundance or occurrence of a species does not, in itself, provide information about the mechanism causing that reduction. For example, reduced abundance or occurrence of a species close to roads is often interpreted as evidence of road avoidance caused by reduced habitat quality (e.g. owing to traffic disturbance) near roads (e.g. [16]). However, it could also be caused by reduced connectivity, causing habitats near roads to be under-used, or it could be caused by increased mortality, as road-kill is more likely to affect individuals with home ranges nearer roads than further from roads [17].

It is also important to note that demonstration of a response to roads does not provide evidence that the demonstrated effect has a larger impact on the population than other potential road impacts. For example, a laboratory experiment might demonstrate impacts of road noise on reproductive success of a species (e.g. [18]). However, the main impact of roads on populations of that species in nature could occur through a mechanism other than traffic disturbance, e.g. road mortality (e.g. [17]). Thus, an appropriate inference from such a study would be that traffic noise likely contributes to the effect of roads on populations of that species. It is important that authors state explicitly in their conclusions that other mechanisms might also be in play, to avoid a situation where managers incorrectly place most weight on mitigating a mechanism that may not be the dominant one.

The inferences made by authors about the mechanisms underlying road effects are important because managers make mitigation decisions based on advice from researchers. Managers are likely to accept the interpretations made by authors about the meaning of their results. Therefore, it is critical that the interpretations of mechanisms made by authors in their Discussions are in fact consistent with their results [7]. It is important to discuss possible alternative interpretations, especially if they affect the choice of mitigation(s).

Our goal was to evaluate the authors' interpretations, to determine whether they explicitly acknowledge all possible mechanisms that are consistent with the responses they measured. To do this, we reviewed the Discussions of studies that evaluated road effects on terrestrial wildlife published between 2012 and 2016. We summarized authors' inferences about the mechanism(s) underlying the measured effects. We determined whether the inferred mechanism(s) are the only mechanisms(s) consistent with the observed responses to roads. We addressed the following questions: (i) what different types of response variables do researchers use to assess road effects on terrestrial animals? (ii) for each type of negative response to roads and traffic, is that response logically consistent with one, two or all three of the mechanisms linking roads to reduced population persistence? (iii) how many of the measured responses in the literature are consistent with one, two or all three of the mechanisms linking roads to population persistence? and (iv) which mechanism(s) are inferred by authors, and do authors discuss all mechanisms that are consistent with their measured responses, or do they favour particular mechanisms? Because of the sequential nature of these questions, we present the methods and results for each question together, in a separate section for each question.

2. Literature search

We reviewed the literature of road and traffic effects on animals having at least one terrestrial life stage, using the Web of Science Core Collection with the search string: '(road* OR highway* OR traffic* OR motorway OR freeway) AND (wildlife* OR fauna* OR animal* OR amphibian* OR reptile* OR mammal* OR bird* OR invertebrate* OR insect*) AND (effect* OR impact* OR affect)'. We restricted our search to 2012–2016 peer-reviewed publications in English in Ecology, Environmental Sciences, Zoology and Biodiversity Conservation categories. We initiated the review in 2017 and chose the preceding 5-year timeframe to characterize the authors' inferences in recent years using a manageable snapshot of the literature. We excluded studies that: used roads as transects to estimate abundance rather than to investigate road effects; had only response variables for which a direction of effect (negative or positive) could not be assigned, e.g. community composition; addressed only methodological questions related to road-kill monitoring; or focused on mitigation planning or evaluation rather than road effects. We only included studies whose inferences were based on quantitative empirical data, i.e. we excluded review papers, anecdotal reports and simulation studies.

Our initial search yielded 1,132 studies. After screening, 307 studies met our inclusion criteria (PRISMA diagram, electronic supplementary material, figure S1). For all included studies, we recorded the direction of responses to roads and/or traffic based on the authors' statements. The 307 studies contained 608 measured responses (electronic supplementary material, table S1). A single study could report more than one response if, for example, it reported responses for more than one species or to different variables for the same species. Of the 608 measured responses to roads or traffic, 327 were negative (54%), 184 were neutral or inconclusive (30%), and 97 were positive (16%). A negative response was one where the response direction would indicate a potential concern for population persistence, such as reduced abundance or reproductive success with increasing traffic. Our review included studies from 46 countries (mostly from North America and Europe, electronic supplementary material, figure S2) and all major terrestrial animal taxa: 43% were mammals; 33% birds; 10% amphibians; 8% invertebrates and 6% reptiles. We included not only studies where the main objective was to estimate responses to roads, but also studies with some other main objective but where the effect of roads or traffic was nevertheless measured, e.g. as a secondary impact, or as a covariate in analyses. We did not observe a higher proportion of negative responses in the former than in the latter (electronic supplementary material, figure S3).

For Question (i), we included all 608 measured responses to roads and traffic, irrespective of the magnitude or direction of response. For Questions (ii)–(iv), we included only the 327 negative responses because only these responses provide information potentially relevant to mitigation, which is only applied in cases of negative impacts.

To identify which of the three major mechanisms are inferred by authors from their results, we looked in the Discussions of reviewed papers. Here our goal was to understand how authors interpreted their results as evidence supporting the major mechanisms underlying road effects on population persistence [8]. We considered that the authors inferred decreased connectivity as the mechanism when they drew conclusions about a barrier, lack of movement, fragmentation, movement restriction or reduced connectivity. We considered that the authors inferred increased mortality as a mechanism when they drew conclusions about direct mortality, road-kills or wildlife–vehicle collisions. We considered that the authors inferred decreased habitat quality as a mechanism when they drew conclusions about habitat selection away from roads or habitat avoidance near roads, and about indicators of reduced habitat quality near roads, such as unsuitable microhabitat or vegetation structure, traffic noise, chemical pollution, stress measures, light pollution, negative edge effects, disturbance and habitat degradation.

3. Question (i): what different types of response variables do researchers use to assess road effects on terrestrial animals?

Studies included a wide variety of response variables, which we divided into 12 categories (figure 1, electronic supplementary material, figure S4). 'Population abundance' includes abundance, density, occurrence and distribution of a species and was by far the most common type of response. 'Stress indicators' includes corticosterone levels and behaviour changes such as vigilance or calling. 'Individual space use' refers to lowered use of territory portions close to a road, while 'homing' refers to reduced probability of returning to a territory when translocated across a road. Most measures of 'species diversity' were species richness. 'Reproduction, growth and survival' are responses of individual animals, while 'Population growth/mean body size' are whole-population responses. 'Genetic difference' refers to genetic difference between populations separated by roads (versus not), while 'genetic diversity' refers to genetic diversity of populations near roads (versus not). Measures of road mortality were divided into three different responses: (i) '*per capita* mortality' when road-kill could be estimated relative to population size or when different sources of mortality were known and so the relative contribution of road-kill to total mortality could be determined; (ii) 'increasing road-kill with increasing traffic' when high-traffic segments had higher road-kill than low-traffic ones and (iii) 'decreasing road-kill with increasing traffic' when high-traffic segments had lower road-kill than low-traffic ones.

4. Question (ii): for each type of negative response to roads and traffic, is that response logically consistent with one, two or all three of the mechanisms linking roads to reduced population persistence?

To answer Question (ii), we worked through the possible inferences about mechanisms that can logically be made from each of the 12 types of responses found in Question (i). To do this, we determined whether a negative response to roads or traffic, using the particular response variable, is logically consistent with each of the potential mechanisms underlying road effects on population persistence.

(a) Responses consistent with only one mechanism

(i) Increasing stress indicators: decreased habitat quality

Indicators of stress in individuals near a road or with increasing traffic are consistent with the inference that decreased habitat quality plays a role in a negative effect of roads or traffic. Change in calling behaviour in response to traffic noise (mostly for birds) was the most measured stress response (about 50% of this category). Many of these studies were experimental, where traffic noise was broadcast and animals' responses were observed (e.g. [19]).

(ii) *Per capita* road-kill rate: increased mortality

A few studies ($n = 5$, e.g. [20]) had sufficient data on the individuals' fates to estimate the proportion of individuals killed by roads (the *per capita* road-kill rate). If this rate is high compared to other causes of mortality, or compared to the reproductive rate, this is consistent with road mortality as a cause for negative effects of roads.

(b) Responses consistent with two mechanisms

(i) Declining reproduction, growth and/or survival of individuals: decreased connectivity and/or decreased habitat quality

Declines in reproduction, growth and/or survival of individuals with proximity to roads or with increasing traffic are consistent with either decreased connectivity or decreased habitat quality as mechanisms. If roads decrease access to resources on the other side of the road (reduced connectivity), this could lead to lower reproduction, growth or survival. Reduced habitat quality near a road could also lead to reduced reproduction, growth or survival through a local shortage of resources or reduced ability to accumulate resources owing to traffic disturbances.

(ii) Increasing road-kill with increasing traffic: decreased connectivity and/or increased mortality

A higher number of road-kills with higher traffic is consistent with the inference that either decreased connectivity or increased mortality play a role in negative effects of roads. Road-kill may increase the overall mortality in the population, leading to lower persistence. When an area of habitat is bounded by high-traffic roads, road-kill may be sufficiently high to prevent immigration and re-colonization after local extinctions.

(iii) Increased genetic difference: decreased connectivity and/or increased mortality

Increased genetic difference between populations or individuals divided by roads is consistent with either decreased connectivity or increased mortality as mechanisms. Reduced connectivity could cause reduced cross-road dispersal, while high road-kill rates could reduce cross-road mating, both resulting in higher genetic difference

(c) Responses consistent with all three mechanisms

(i) Decreased population abundance

Decreased population abundance, the most common indicator of population persistence, is consistent with any of the mechanisms. Reduced connectivity could reduce abundance owing to lack of immigration. Road mortality could directly reduce abundance near roads and/or in a landscape with high road density. Reduced habitat quality could lead to stress causing reduced growth, reproduction, survival or avoidance of habitats near roads, any of which could reduce population abundances.

(ii) Reduced species richness or diversity

If roads and traffic affect the abundance/occurrence of several species in an area, this can result in a reduced species richness or diversity. This is therefore consistent with any of the mechanisms (see §4c(i)).

(iii) Decreased individual space use

Individuals can avoid areas near roads because of decreased habitat quality, e.g. owing to traffic disturbance. Less obviously, a pattern of lower space use near a road might be caused by past road mortality (electronic supplementary material, figure S5). Of those individuals whose territories are close to a future road, the ones with their centre of activity closer to the road are more likely to be road-killed. As we measure space use relative to the road only after these individuals are already dead, we observe a pattern of space use that is centred away from the road as an artefact of past mortality. Finally, reduced space use near roads (for whatever reason) could result in fewer cross-road movements, resulting in lower immigration to empty or under-used habitats. Therefore, reduced individual space use is also consistent with reduced connectivity as a mechanism underlying negative road impacts.

(iv) Decreased genetic diversity

Decreased genetic diversity is consistent with all mechanisms. If roads reduce connectivity, then alleles lost by genetic drift on one side of the road may not be reintroduced to the population by immigrants from the other side, reducing genetic diversity. If road-kill reduces population size, genetic diversity will decrease owing to drift [21]. Reduced habitat quality could similarly lead to reduced survival causing reduced abundance, again reducing genetic diversity by drift.

(v) Decreasing road-kill with increasing traffic

To the extent that road-kill numbers are an index of relative abundance of the species near the road, decreasing road-kill with increasing traffic could indicate that population abundance declines with increasing traffic: fewer animals are road-killed because there are fewer animals available [22]. Therefore, a decline in abundance with increasing traffic is consistent with any of the mechanisms (see §4c(i) above).

(vi) Reduced homing

Reduced homing refers to fewer individuals returning to their home territories after cross-road translocation than when translocated an equivalent distance not containing a road. Translocated animals might not return to their territories because the road is a barrier to their movement, which is

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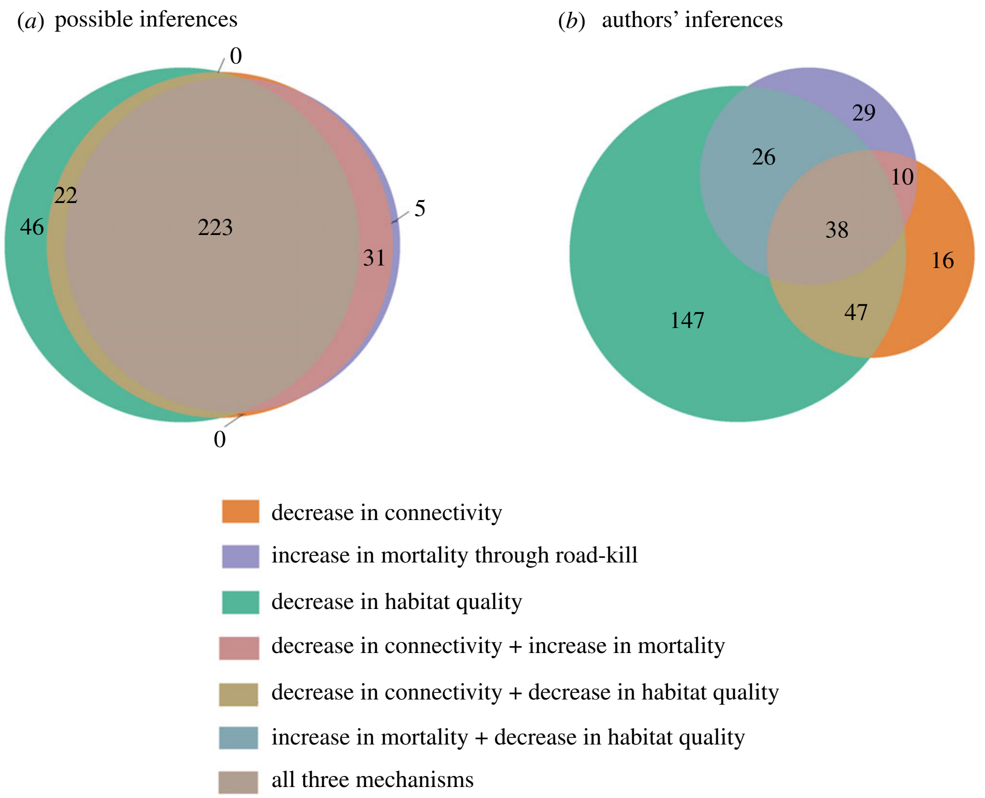

Figure 2. The numbers of measured responses to roads and traffic that are consistent with each of the three mechanisms linking roads to population persistence (*a*) versus the number of mechanisms discussed by authors in their Discussions, based on those same measured responses (*b*). The responses measured in almost all studies are consistent with multiple mechanisms. By contrast, most authors discuss a single mechanism even though more than one is consistent with their results.

consistent with decreased connectivity as an underlying mechanism. A translocated animal also might not return to its home territory because it was road-killed while trying to return, consistent with increased mortality as a mechanism. Or, translocated individuals might not attempt to return to their territories if they avoid low-quality habitats near roads, consistent with reduced habitat quality as a mechanism.

(vii) Declining population growth rate or declining mean body size

Decreased connectivity could reduce resource availability, leading to reduced overall population growth rate or reduced mean body size. Increased road-kill directly removes individuals from the population, reducing the population growth rate and the average body size in the population. The latter occurs even if the *per capita* road mortality rate is independent of body size, because when young individuals are killed, their potential larger selves are also killed. Finally, reduced habitat quality could lead to reduced individual growth or survival through a shortage of resources, reducing overall population growth rate or mean body size.

5. Question (iii): how many of the measured responses in the literature are consistent with one, two or all three of the mechanisms linking roads to population persistence?

For Question (iii), we used the arguments elaborated in Question (ii) to determine, for each negative response to roads and traffic observed in our literature search, whether that response was consistent with one, two or all three of the mechanisms linking roads to population persistence. As our goal was to assess the authors' inferences, we did not evaluate the quality of study design, data collection, or analysis of the studies themselves; we took the study results at face value. Of the 327 negative responses, 51 were consistent with one mechanism, 51 with two mechanisms and 223 were consistent with all three mechanisms (figure 2*a*).

6. Question (iv): which mechanism(s) are inferred by authors, and do authors discuss all mechanisms that are consistent with their measured responses, or do they favour particular mechanisms?

Question (iv) is our main objective. Here we were interested in the authors' inferences about the three main mechanisms from studies that found negative effects of roads or traffic (irrespective of whether road effects were the primary goal of the study; see §2). We wanted to know whether authors focused on particular mechanisms exclusively or acknowledged all mechanisms that were logically consistent with their results. To do this, we searched the Discussions of each study for the authors' inferences.

We found a strong difference between the mechanisms that are logically consistent with the measured responses and the mechanisms inferred by authors (figure 2*a* versus *b*). Authors generally discussed only a subset of the mechanisms that were consistent with their responses. Authors inferred that 192 measured responses were consistent with only one mechanism (compared to 51 possible), that 83 were consistent with two mechanisms (compared to 53 possible), and that only 38 were consistent with all three mechanisms (compared to 223 possible). For 14 measured responses (which included *per capita* road-kill, decreased population abundance, decreased species diversity and decreased individual space use), the authors did not make inferences about road impact mechanisms. Authors demonstrated a strong tendency to interpret their results as consistent with reduced habitat quality as the only mechanism linking roads to population persistence (147 responses compared to 46 possible). This tendency is especially noticeable when we look at the inferences based on the responses that are consistent with all three mechanisms. Here, reduced habitat quality was 2.4 times as likely to be inferred as a mechanism compared to reduced connectivity, and 2.9 times as likely to be inferred as a mechanism compared to increased road-kill (electronic supplementary material, figure S6).

In addition, authors showed a very strong tendency to mention only decreased connectivity when both decreased connectivity and increased mortality were consistent with the measured responses. In these cases, authors were 5.2 times as likely to mention decreased connectivity as the mechanism linking roads and traffic to population persistence (electronic supplementary material, figure S6).

7. Discussion

We found that most (84%) of the measured negative responses to roads are consistent with more than one of the major mechanisms linking roads to population persistence: decreased connectivity, increased mortality and decreased habitat quality. By contrast, most authors mentioned only a single mechanism in their Discussions. While we refrain from describing individual examples, the information extracted from the studies is available in electronic supplementary material, table S1. Thus, it appears that most authors do not recognize all the mechanisms that are consistent with their measured responses. This suggests that over-interpretation of results is common in road ecology research.

Our results suggest two strong tendencies in authors' inferences about the mechanisms underlying road impacts. First, reduced habitat quality is consistently favoured as the most likely mechanism causing negative effects on population persistence, even when both of the two other major mechanisms are also consistent with the responses measured. Second, when both decreased connectivity and increased mortality are consistent with the responses measured, authors show a very strong tendency to conclude that reduced connectivity is the main mechanism linking roads and traffic to population persistence. Therefore, authors infer a role of connectivity less often and a role of mortality *much* less often than is logically consistent with their results.

The failure of researchers to consider multiple hypotheses is common in ecological research [23], leading to a general problem of weak inference [24]. From our review, it appears that the road ecology literature is no exception. This might happen for several reasons, from cognitive bias to practical barriers and logistical constraints [23], or even owing to the pressure for fast publication. However, explicit recognition of multiple hypotheses is particularly relevant in the context of an applied science such as road ecology, where managers use the stated inferences from scientific studies to design mitigation. For example, if an author states an observed road effect is consistent with reduced connectivity as the underlying mechanism, then a manager will conclude that mitigation for improved connectivity is needed, e.g. wildlife passages. The manager's conclusion would be different if the authors acknowledged that their measured response was also consistent with road mortality. Therefore, the current literature may be leading to inappropriate decision-making by road managers.

Selecting appropriate mitigation for reducing effects of roads on wildlife populations depends on identifying the correct and strongest mechanism(s) that underlie the effects of roads on the wildlife population in question. Given their inferences about mechanisms, we speculate that road ecologists over-emphasize mitigation measures to reduce traffic disturbances such as noise and measures to allow animal movements across roads such as wildlife passages, and that they under-emphasize measures to keep animals off roads such as wildlife fencing. We did a preliminary evaluation of this by conducting a *post hoc* screening for mitigation recommendations in 30 randomly selected Discussions of studies showing negative responses to roads that were logically consistent with all three mechanisms. Two thirds (19 studies) provided mitigation recommendations, a proportion similar to the 75% found by [7]. Mitigation for decreased habitat quality was recommended three times more often than mitigation for road mortality and two times more often than mitigation for decreased connectivity. We conclude that a more complete synthesis similar to our preliminary evaluation is needed to test if the unconscious tendencies of road ecologists are resulting in inappropriate advice for mitigation. This is especially concerning because installed measures are usually simply assumed to be effective, or their effectiveness is not adequately monitored [25,26].

Our initial goal for this study was to use the literature to determine the relative importance of different mechanisms in causing negative road effects on animal populations. We had planned to compare effect sizes for road responses associated with different mechanisms, providing a quantitative evaluation of their relative roles. However, we were unable to meet that goal because most measured responses were consistent with multiple mechanisms linking roads and traffic to population persistence, and so the relative contributions of the three main mechanisms remain unknown. This is because most of these studies were not designed to compare multiple mechanisms [23,24], but rather they were designed to determine whether a single mechanism might occur. We note here that even the measured responses that are consistent with only one mechanism are not helpful for meeting our initial goal. For example, about half of these studies investigated the effects of traffic noise on various species responses. Many of them were experiments in which traffic noise was broadcast and animal responses were observed, often in laboratory conditions. While such studies do show that a species can respond negatively to traffic noise, they do not show that the effects of traffic noise (an aspect of habitat quality) are the main mechanism responsible for negative effects on the population. These effects could still be mainly caused by either decreased connectivity or increased mortality. Therefore, we are currently unable to draw conclusions about the relative importance of the three main mechanisms in causing the negative effects of roads on abundance and ultimately on population persistence.

We acknowledge that our ability to correctly categorize the mechanism(s) inferred by authors depended on our ability to correctly interpret the intended meaning of words and phrasing in the Discussions. Overall, we are confident in these interpretations, but some ambiguous wording may have led to a few inaccuracies in our categorizations (see §2). We also acknowledge that some authors may know of additional relevant information, which they did not include in their Discussions, suggesting that mechanism(s) other than the one(s) they emphasized are not at play in their system. For example, there may be site- or species-specific contexts that allow authors to infer which is the mechanism at play. Even in such cases, we suggest that authors should mention other possible mechanisms consistent with their responses and explain why these other mechanisms are not at play in their case. Authors should be explicit about the evidence supporting their interpretations so that readers are aware of all the information needed to make such inferences. This problem was recently highlighted in a review of African road ecology studies [7] showing that over 30% of authors recommended mitigation without evidence from their results. Likewise, reviewers and editors need to ensure the papers they handle have well-supported inferences, especially in a field with strong practical implications such as road ecology.

We also acknowledge that our description of the three mechanisms is somewhat simplified, as more complex interactions and indirect effects are possible. For example, increasing mortality with increasing traffic could be consistent with reduced habitat quality as a mechanism, if decreased habitat quality causes an increase in movement and therefore increases the road-kill likelihood. As a second example, if road mortality is sex-biased, this could result in reduced reproduction, in which case a reduced reproductive rate near roads would be consistent with road mortality as a mechanism. Other such examples are possible. These interactions and indirect effects reinforce our main conclusion that, while most measured responses are consistent with all mechanisms, most authors infer only one of them, thus calling into question the quality of inferences in road ecology research.

Moving forward, we suggest the following recommendations for road ecology researchers. First (and easiest), researchers could think carefully about alternative possible mechanisms before concluding that their research results support a single mechanism, and especially before offering mitigation advice. In making such inferences, they should explicitly include all relevant information from previous or related work. In addition, reviewers and editors should encourage authors in this direction. Second (and much more difficult), researchers could design studies that follow the principles of strong inference [24], with predictions that allow one to distinguish among alternative hypotheses or mechanisms (e.g. [17]) and, ideally, to quantify their relative effects. Such study designs are admittedly difficult in road ecology where all mechanisms linking roads to population persistence are related to traffic volume, sometimes in complex ways, and are therefore difficult to study independently. Future work is needed to elucidate possible study designs, but it may turn out that designs that can distinguish among the road impact mechanisms are rare. In this case, and in the meantime, the most prudent course is to be transparent and recognize the limitations of existing studies, to admit that we do not know which is the dominant mechanism underlying road effects on population persistence and, therefore, to recommend that mitigation target all possible mechanisms.

Data accessibility. The list of reviewed studies and corresponding results for each study is available in the supplementary material (electronic supplementary material, table S1).

Authors' contributions. L.F., F.Z.T. and T.R. designed the study. F.Z.T. performed the review search and analyses. F.Z.T. did the screening and data extraction for all studies. Classification of response variables was discussed among all authors, and studies difficult to classify were also discussed among all authors. Discussions among all authors contributed to the subsequent conceptual and theoretical development of the study. F.Z.T. wrote the first draft of the manuscript, and all authors contributed substantially to revisions.

Competing interests. We declare we have no competing interests.

Funding. F.Z.T. was funded as a postdoctoral fellow at the Geomatics and Landscape Ecology Laboratory (GLEL), through a grant from the Natural Sciences and Engineering Research Council of Canada (NSERC) to L.F.

Acknowledgements. We thank the members of the Road and Railroad Ecology Group (NERF-UFRGS) for suggestions on figures in a previous version of this manuscript. We also thank the editors and reviewers who made comments on previous versions of this manuscript.

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