Global Ecology and Conservation 19 (2019) e00661

Contents lists available at ScienceDirect

Global Ecology and Conservation

journal homepage: http://www.elsevier.com/locate/gecco

Short Communication

Beware that the lack of wildlife mortality records can mask a serious impact of linear infrastructures

Fernando Ascensão [a], [b], [c], [*], Andreas Kindel [d], Fernanda Zimmermann Teixeira [d], [e], Rafael Barrientos [a], [b], [f], Marcello D'Amico [b], [g], [h], Luís Borda-de-Água [a], [b], Henrique M. Pereira [a], [b], [i], [j]

[a] CIBIO/InBio, Centro de Investigação em Biodiversidade e Recursos Genéticos, Laboratório Associado, Universidade do Porto, Campus Agrário de Vairão, 4485-661, Vairão, Portugal
[b] CIBIO/InBio, Centro de Investigação em Biodiversidade e Recursos Genéticos, Laboratório Associado, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017, Lisbon, Portugal
[c] Department of Conservation Biology, Estación Biológica de Doñana (EBD-CSIC), Sevilla, Spain
[d] Núcleo de Ecologia de Rodovias e Ferrovias, Departamento de Ecologia, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Brazil
[e] Programa de Pós-Graduação em Análise e Modelagem de Sistemas Ambientais, Universidade Federal de Minas Gerais, Belo Horizonte, Brazil
[f] Department of Biodiversity, Ecology and Evolution, Universidad Complutense de Madrid, C/ José Antonio Novais, 12, E-28040, Madrid, Spain
[g] REN Biodiversity Chair. CIBIO/InBIO, Centro de Investigação em Biodiversidade e Recursos Genéticos, Universidade do Porto, Portugal
[h] Department of Environmental Chemistry, Institute of Environmental Assessment and Water Research (IDAEA-CSIC), Barcelona, Spain
[i] German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Germany
[j] Institute of Biology, Martin Luther University Halle-Wittenberg, Am Kirchtor 1, 06108 Halle (Saale), Germany

ARTICLE INFO

Article history:
Received 26 March 2019
Received in revised form 9 May 2019
Accepted 9 May 2019

Keywords:
Barrier effect
Fences
Population depletion
Power lines
Railways
Roadkill
Roads
Transportation networks

ABSTRACT

Linear infrastructures (e.g. roads, railways or power lines) promote a myriad of negative impacts on wildlife around the world, of which direct mortality is the most visible one. When high mortality rates are found, mitigation measures are often discussed and applied. On the other hand, the lack of mortality is commonly interpreted as evidence of low impact on wildlife. We argue that the lack of mortality may actually mask two pervasive effects of linear infrastructures on animal populations: past massive mortality, causing local extinctions, or strong barrier effects due to the inability or reluctance of individuals to traverse the infrastructure corridor. In order to obtain a sound impact assessment of the linear infrastructures on wildlife, research is needed that integrates long-term mortality data with information on the abundance of the focal species, their genetic patterns and movement behavior. We discuss the implications of these impacts for both infrastructures and landscape management.

1. Introduction

Linear infrastructures such as roads, railways, power lines, water channels, pipelines, wind farms and fences are common human-made features in the globe, spreading across nearly all of its surface (Biasotto and Kindel, 2018; Borda-de-Água et al.,

---

[*] Corresponding author. Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017, Lisboa, Portugal.
E-mail address: fjascensao@cibio.up.pt (F. Ascensão).

https://doi.org/10.1016/j.gecco.2019.e00661

2017; Ibisch et al., 2016; Jakes et al., 2018). Despite their potential value to human living and development, they inflict diverse negative impacts on biodiversity, of which the most visible is direct mortality through collisions with vehicles, and collision or electrocution with overhead wires: impressive mortality rates caused by these infrastructures have been reported for several animal groups, namely on roads (D'Amico et al., 2015), railways (Borda-de-água et al., 2017), power lines (Barrientos et al., 2011), water channels (Peris and Morales, 2004), and wind farms (Loss et al., 2013). For example, bird mortality in the United States is estimated to range from 89 to 340 million individuals for collisions with motor vehicles and from 12 to 64 million individuals annually, respectively for electrocution and collisions with power lines (Loss et al., 2014a, 2014b).

High mortality rates can lead to a population depletion effect and ultimately to extinctions (Beebee, 2013). Hence, not surprisingly, linear infrastructures' mitigation has been largely based on research focusing on mortality impacts. A common approach is to identify sections that have a higher risk of mortality, which are then recommended to be prioritized for implementing mitigation measures, such as the installation of exclusionary fences linked to crossing structures along roads or railways (Clevenger et al., 2001) or wire marking on power lines (Barrientos et al., 2012). We argue that mitigation prioritization should not be directly linked to mortality counts solely, as it can compromise the success of management plans if other important processes are not considered, namely *i*) previous massive mortality rates causing significant reductions of animal population densities on surrounding habitats or, even, local extinctions; and *ii*) inability or reluctance of individuals to cross the linear infrastructures.

Casualties may also become unnoticed due to intrinsic factors related to the carcass characteristics or observers particularities, such as the carcass persistence time and detectability (Barrientos et al., 2018; Santos et al., 2016; Teixeira et al., 2013). However, a considerable amount of literature has already analyzed and discussed these biases in the context of different linear infrastructures, including roads (Santos et al., 2016; Teixeira et al., 2013), power lines (Ponce et al., 2010) or wind-farms (Kunz et al., 2007), and it is therefore outside the scope of this text. Here we assume that the sampling design when surveying a linear infrastructures guaranteed the detection of casualties where and when they occurred. In the following sections, we address how previous massive mortality and the absence of crossings can lead to low mortality detection, highlight research needs for a better assessment of the impacts of linear infrastructures, and discuss their implications for resource managers and policy makers.

2. Population depletion due to massive mortality

When per-capita mortality is not offset by an increase in per-capita recruitment, the growth rate of populations can be seriously affected, ultimately leading to their disappearance or to a strong population depletion in the surrounding areas (Teixeira et al., 2017). Such effects have been documented in empirical studies reporting significant population depletions or even local extinctions directly related to the mortality impact of linear infrastructures. For example, Jones (2000) found that the upgrade of a Tasmanian road led, in few years, to the increase of road-kill rates and the local extinction of eastern quolls (*Dasyurus viverrinus*; Fig. 1A).

Similar examples concerning power lines include the steep population decline due to the electrocution of eagle owls (*Bubo bubo*) in an area of the Italian Apennines (Sergio et al., 2004); and a population of blue crane (*Anthropoides paradiseus*) in the Western Cape of South Africa which is estimated to be reduced by 12% annually due to power line collisions alone (Shaw et al., 2010). Even a low mortality risk can contribute significantly to a population decline, as shown for the koala (*Phascolarctos cinereus*), threatened by roadkill in the Iluka Peninsula of Australia (Lunney et al., 2002), and for the great bustard *Otis tarda*, threatened by power-line collisions in both England and Portugal (Osborne, 2005; Pinto et al., 2005). Also, a long-term study that started in England in 1990 on the European common toad (*Bufo bufo*) showed a continuing decrease in the number of road-killed individuals along the surveyed roads (despite the increase of traffic volume), which was significantly correlated with the population decline in the surrounding ponds (Cooke, 2011).

Hence, infrastructures bisecting areas where populations have already experienced a significant decline due to roadkill, electrocution or collision with power lines are expected to have low mortality rates. However, this outcome may erroneously be interpreted as an evidence of a low impact of infrastructures on wildlife, whereas it actually resulted from a previous detrimental effect.

3. Not crossing the infrastructure corridor

Another circumstance that may result in a lack of mortality occurs when the linear infrastructure imposes a strong barrier effect on animal movement. This barrier effect can stem from different mechanisms, namely the animals may be unable to transpose the infrastructure corridor as it represents an insurmountable physical obstacle, or the individuals do not cross the infrastructure due to avoidance behavior. For example, translocation experiments carried out in Virginia (USA) with the red-backed salamander (*Plethodon cinereus*; Fig. 1B) showed that roads can significantly reduce their return rate, particularly where steep roadside verges are present (Marsh et al., 2005). In North Carolina (USA), experiments showed that railways are significant barriers for the eastern box turtles (*Terrapene carolina*) (Kornilev et al., 2006).

Other species tend to avoid crossing gaps in vegetation, particularly those caused by roads or power lines. For example, vegetation clearings as narrow as 50 m have been shown to constrain bird movement (Develey and Stouffer, 2008). Likewise, several small mammal species are known to avoid open areas, probably due to predation risk, and even dirt roads may represent deterrent features for animal movement (Ascensão et al., 2017). This gap effect can be worse for arboreal species,

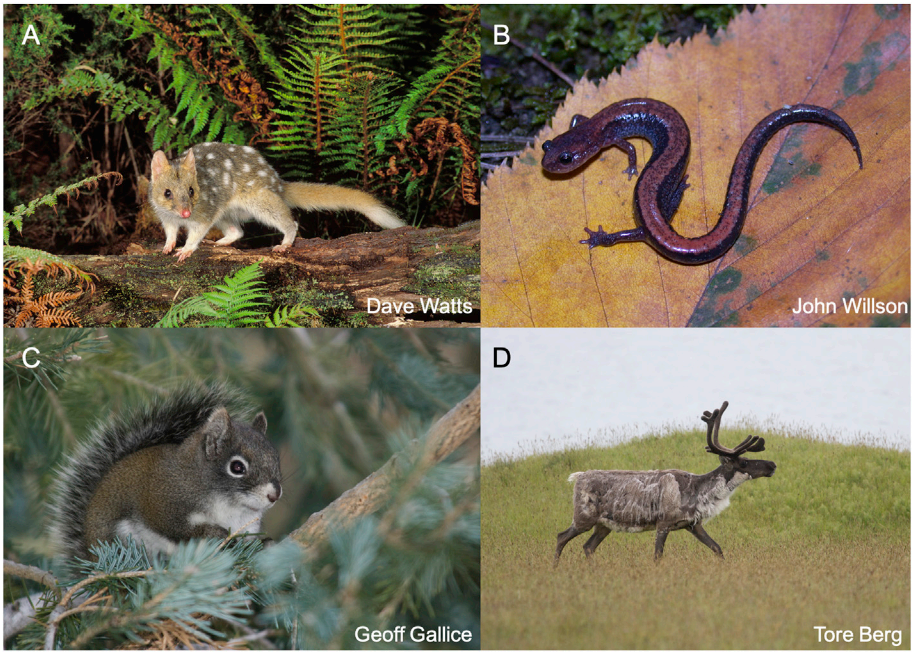

Fig. 1. Example of species studied in research related to linear infrastructure impacts on biodiversity. A) Eastern quoll (*Dasyurus viverrinus*) is heavily impacted by roadkill in Tasmania; B) Red-backed salamander (*Plethodon cinereus*) has its movements impaired by steep roadsides; C) Mount Graham red squirrel (*Tamiasciurus hudsonicus grahamensis*) is reluctant to cross forest gaps caused by roads, regardless of traffic volume; D) Reindeer (*Rangifer tarandus*) is thought to perceive the 'corona' effect of power lines. Credits (A to C): Dave Watts, John Willson, Geoff Gallice, Tore Berg.

which typically spend a great part of their time feeding, nesting or moving through trees. For example, forest roads are known to act as a barrier for the Mount Graham red squirrel (*Tamiasciurus hudsonicus grahamensis*; Fig. 1C), an endangered canopy obligate species, which is generally reluctant to cross forest gaps, including those caused by roads regardless of traffic volume (Chen and Koprowski, 2016).

Some species also avoid the vicinity of infrastructures, thereby intensifying the habitat loss and barrier effects. Such avoidance behaviors can have important repercussions on accessing resources, including mates or food. Even generalist species as red deer (*Cervus elaphus*) and wild boar (*Sus scrofa*) seem to avoid the road proximity (including along unpaved roads), as shown at Doñana Biosphere Reserve, Spain (D'Amico et al., 2016). Another example concerns the Mongolian gazelles (*Procapra gutturosa*) and Asiatic wild ass (*Equus hemionus*) avoiding crossing fenced railways (despite their capacity to trespass them), disrupting their long distance migration and therefore their access to foraging areas, increasing their winter mortality due to starvation (Ito et al., 2013). Most surprisingly, some mammals, such as for example the reindeer (*Rangifer tarandus*; Fig. 1D), have been suggested to avoid power lines due to the ultraviolet discharges occurring as standing corona along cables or irregular flashes on insulators (Tyler et al., 2014).

Overall, some species are unlikely to be killed in linear infrastructures at any timeframe after its construction. Although the population size may remain stable, i.e. less affected by mortality, these species likely experience a strong barrier effect, which may reduce the accessibility to resources, therefore jeopardizing the survival of entire populations (Eigenbrod et al., 2008). Moreover, the barrier effect may prevent the exchange of gene flow between populations, with further negative demographic and genetic structuring consequences, including the loss of genetic variation due to random drift and increased inbreeding (Holderegger and Di Giulio, 2010).

4. Research needs

Future research addressing wildlife-linear infrastructure interactions should strive to better understand how the mortality patterns (including the lack of mortality) relate with the spatial patterns of species and landscape connectivity. We suggest a standard protocol to be integrated in infrastructure-related research to measure species occurrence and abundance in control and impact sites. Impact sites should be in the vicinity of the studied infrastructure (where vicinity is a distance not superior to half of the focal species home range) and control sites should be far from any other infrastructure that may cause a positive or negative effect on the focal species population (i.e., controlling for similarity of relevant environmental factors) (Roedenbeck et al., 2007). The species distribution and abundance can be obtained (depending on the focal species) for example by performing transect surveys looking for signs or live animals, or implementing a grid of camera traps (Howe et al., 2017), both in control and impact sites.

Moreover, a great concern should also be dedicated to understanding the animal movement behavior toward the different infrastructures and incoming vehicles, as well as species responses to mitigation alternatives. Today, an array of tracking devices is available and their cost is decreasing substantially, bringing the animal movement discipline toward a next level (Kays et al., 2015). This implies that in the near future we will be able to categorize the behavioral responses of a broad range of species if adequately designed studies are implemented, i.e. we will be able to quantify the barrier effect of different infrastructures. On the other hand, collecting and analyzing genetic samples (e.g. hair tubes) may provide valuable complementary information regarding the gene flow of populations across the infrastructures. Again, it is important to obtain data from areas impacted by the infrastructure, and from areas devoid of impacts. Importantly, in all cases, a sufficient number of replicates must be considered (of both control and impact sites), in order to obtain sound empirical data to allow a robust comparison across site types and timeframes.

A good understanding of the distribution and abundance, and movement patterns, not only in the infrastructure vicinity but also at areas farther away from the infrastructure, can provide the necessary information to assess the population condition and trends, and with that a better planning and minimization of the impacts. Such knowledge is imperative for threatened species, but also to common ones for which the impact of linear infrastructures is often overlooked, and the resulting population decline or structuring may be unnoticed. Yet, such effects can result in significant cascading impacts for the entire ecosystem (Gaston and Fuller, 2008).

When the infrastructure under study is yet to be constructed, and in line with previous recommendations (Baxter-Gilbert et al., 2015; Roedenbeck et al., 2007), a Before-After-Control-Impact research design is preferable, as it provides the highest inferential strength (Roedenbeck et al., 2007). In this approach, the distribution, abundance and movement patterns are measured in impact sites and control sites, both before and after the construction time. However, this requires knowing in advance where and when a given infrastructure is being constructed, and the synchronization of the construction and research timings, which in most cases are difficult requisites to accomplish.

When it is not possible to study the impact sites previous to the construction phase, the Control-Impact design provides the alternative with the best inferential strength (Roedenbeck et al., 2007). In this design, both populations inhabiting the infrastructure vicinity and the control sites are measured simultaneously. Depending on the changes of the patterns of mortality, movement, and abundance on control and impact sites, one can infer if and of what type of impact the infrastructure has at the population level. When a high mortality is recorded, coupled with no avoidance behavior and a lower abundance in impact sites, suggest that the infrastructure is driving a depletion effect and acting as a sink habitat. Conversely, when a low mortality is recorded, which is our focus here, and is coupled with no avoidance behavior and similar abundance between control and impact sites, suggests that individuals are able to cross safely and/or avoid incoming vehicles (Fig. 2). Detecting a past depletion effect may become more challenging. However, one can suspect of a past depletion effect when recording a low mortality rate together with lower abundance in impact sites and no signs of avoidance movement behavior (Fig. 2). Finally, a low mortality coupled with an avoidance behavior toward the infrastructure proximity, suggest a strong barrier effect (Fig. 2).

5. Implications for infrastructure managers and policy makers

Managers and policy makers should be aware that the lack of mortality along linear infrastructures may be the outcome of population depletion or a strong barrier effect on animal movement. This can have important consequences for animal conservation and mitigation planning. Mitigation locations should not be based solely on mortality hotspots as these patterns are highly variable along time (Santos et al., 2017), and may fail to identify critical areas when populations are already depleted (Teixeira et al., 2017). Moreover, mitigation targeting species that are recurrently killed in infrastructures may fail to

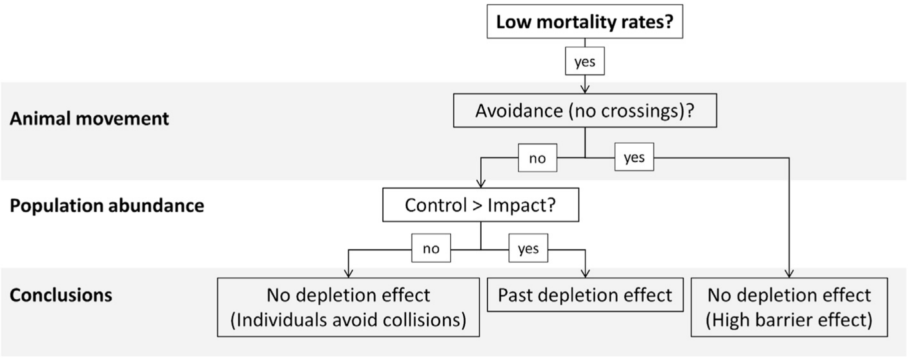

Fig. 2. Paths leading to the most likely conclusions about the impact of an infrastructure on animal populations using a Control Impact design and considering the patterns of mortality, the movement behavior of individuals towards the infrastructure, and abundance of the species in control and impact sites. For example, a low mortality rate, combined with no evidence of individuals avoiding crossing the infrastructure and a greater abundance at control sites relative to impact sites, suggest a past depletion effect due to mortality in the infrastructure.

address the specific needs of species that are unable or unwilling to cross the infrastructure corridor. For example, upgrading road underpasses may fail to restore the connectivity for arboreal obligate species, and installing flight diverters in power lines may be useless for forest birds that are unwilling to cross vegetation clearings.

On the other hand, if the information on species distribution and abundance, together with movement is available, researchers and practitioners can evaluate how the infrastructures interfere with the population dynamics and with that on the habitat functional connectivity, i.e. the degree to which the linear infrastructures (and other landscape elements) actually promote or impede the movement of organisms and processes (Taylor et al., 1993). Such evaluation may allow identifying more problematic infrastructures' sections, as those that bisect areas of higher functional connectivity. We are aware that such an improvement in data collection as suggested demands an increase in resources, including labor, time and budget. Probably due to this increase in resource requirements, to our knowledge, there are still few long-term empirical studies on the effects of infrastructures on population persistence and dynamics (Cooke, 2011). On the other hand, studies focusing on mortality along linear infrastructures normally span for a limited period, usually one year. As a result, the ecological interpretation of their findings is limited. Hence, it is crucial to integrate the necessary budget and research timelines within the infrastructure construction planning, in order to allow for such data collection.

We suggest that the planning and location of mitigation measures should focus more on habitat functional connectivity, targeting the linkage between habitat areas that may even be farther away from the infrastructure and yet play an important role in the population viability (Clauzel, 2017). Mitigation of linear infrastructures may better serve conservation by targeting those sections intercepting higher functional connectivity corridors. Note that for more recently built infrastructures, high mortality sections should coincide with areas of higher functional connectivity (Grilo et al., 2011). However, for older infrastructures, areas of higher functional connectivity or with more suitable habitat are not necessarily those with higher mortality (Teixeira et al., 2017), reinforcing the need to collect the information on distribution and abundance and movement patterns.

Landscape management could also plan different landscape features to lead animals towards sections of the infrastructure with a lower probability of mortality or where mitigation is already in place. Naturalizing the crossing structures by placing vegetation, logs and rocks may help individuals to perceive the habitat continuity between both sides of the infrastructure (Clevenger, 2012). Nevertheless, it is fundamental to address multi-specific requirements for animal movement, from ground-dwelling to arboreal obligate species, again not only in the surroundings of the infrastructures but at the landscape context. It should be noted that connectivity restoration is expected to become a major challenge in face of the expected modifications in the spatial distribution of environmental conditions due to climate change (Clevenger, 2012; Lister et al., 2015).

6. Conclusion

Linear infrastructures' networks are expanding rapidly worldwide and a bulk of research regarding their impacts on biodiversity has emerged in recent years, particularly the study of direct mortality. However, to date there has been no integrative study aiming to understand at which extent the lack of mortality may mask other pervasive impacts, as the population depletion or strong barrier effects. Future research should integrate long-term information of mortality patterns (including their absence) with the information on species distribution and abundance, as well as the movement behavior and genetic patterns at different distances from the linear infrastructures. This information can provide landscape and infrastructure managers with detailed knowledge on what type of mitigation action is required in each site. Furthermore, it can assist in preliminary planning steps, knowing in advance where major impacts may arise, particularly in face of the expected species' range shifts due to climate change effects.

Funding

FA and RB were funded through post-doctoral grants from Infraestruturas de Portugal (IP Biodiversity Chair). FA was also funded through a post-doctoral grant from Fundação para a Ciência e a Tecnologia (FCT, SFRH/BPD/115968/2016). FZT was funded by a post-doctoral fellowship from Fundação de Aperfeiçoamento de Pessoal de Nível Superior (PNPD/CAPES). MD was funded through a post-doctoral grant from Redes Energéticas Nacionais and FCT (REN Biodiversity Chair) and a Juan de la Cierva Formación post-doctoral grant from MINECO (Ministerio de Economía y Competitividad). LBA was funded by Portuguese national funds through the FCT — Fundação para a Ciência e Tecnologis, I.P.

References

Ascensão, F., Lucas, P.S., Costa, A., Bager, A., 2017. The effect of roads on edge permeability and movement patterns for small mammals: a case study with Montane Akodont. Landsc. Ecol. 32, 781—790. https://doi.org/10.1007/s10980-017-0485-z.

Barrientos, R., Alonso, J.C., Ponce, C., Palacín, C., 2011. Meta-analysis of the effectiveness of marked wire in reducing avian collisions with power lines. Conserv. Biol. 25, 893—903. https://doi.org/10.1111/j.1523-1739.2011.01699.x.

Barrientos, R., Martins, R.C., Ascensão, F., D'Amico, M., Moreira, F., Borda-de-Água, L., 2018. A review of searcher efficiency and carcass persistence in infrastructure-driven mortality assessment studies. Biol. Conserv. 222, 146—153. https://doi.org/10.1016/j.biocon.2018.04.014.

Barrientos, R., Ponce, C., Palacín, C., Martín, C.A., Martín, B., Alonso, J.C., 2012. Wire marking results in a small but significant reduction in avian mortality at power lines: a BACI designed study. PLoS One 7 e32569. https://doi.org/10.1371/journal.pone.0032569.

Baxter-Gilbert, J.H., Riley, J.L., Lesbarrères, D., Litzgus, J.D., 2015. Mitigating reptile road mortality: fence failures compromise ecopassage effectiveness. PLoS One 10 e0120537. https://doi.org/10.1371/journal.pone.0120537.

Beebee, T.J.C., 2013. Effects of road mortality and mitigation measures on Amphibian populations: Amphibians and roads. Conserv. Biol. 27, 657–668. https://doi.org/10.1111/cobi.12063.

Biasotto, L.D., Kindel, A., 2018. Power lines and impacts on biodiversity: a systematic review. Environ. Impact Assess. Rev. 71, 110–119. https://doi.org/10.1016/j.eiar.2018.04.010.

Borda-de-água, L., Barrientos, R., Beja, P., Pereira, H.M., 2017. Railway Ecology. Springer. https://doi.org/10.1007/978-3-319-57496-7.

Chen, H.L., Koprowski, J.L., 2016. Barrier effects of roads on an endangered forest obligate: influences of traffic, road edges, and gaps. Biol. Conserv. 199, 33–40. https://doi.org/10.1016/j.biocon.2016.03.017.

Clauzel, C., 2017. Evaluating and mitigating the impact of a high-speed railway on connectivity: a case study with an Amphibian species in France. In: Borda-de-Água, L., Barrientos, R., Beja, P., Pereira, H.M. (Eds.), Railway Ecology. Springer International Publishing, pp. 215–228. https://doi.org/10.1007/978-3-319-57496-7_13.

Clevenger, A.P., 2012. Mitigating continental-scale bottlenecks: how small-scale highway mitigation has large-scale impacts. Ecol. Restor. 30, 300–307. https://doi.org/10.3368/er.30.4.300.

Clevenger, A.P., Chruszcz, B., Gunson, K.E., 2001. Highway mitigation fencing reduces wildlife-vehicle collisions. Wildl. Soc. Bull. 646–653.

Cooke, A.S., 2011. The role of road traffic in the near extinction of Common Toads (*Bufo bufo*) in Ramsey and Bury. Nat. Cambs. 53, 45–50.

D'Amico, M., Périquet, S., Román, J., Revilla, E., 2016. Road avoidance responses determine the impact of heterogeneous road networks at a regional scale. J. Appl. Ecol. 53, 181–190. https://doi.org/10.1111/1365-2664.12572.

D'Amico, M., Román, J., de los Reyes, L., Revilla, E., 2015. Vertebrate road-kill patterns in Mediterranean habitats: who, when and where. Biol. Conserv. 191, 234–242. https://doi.org/10.1016/j.biocon.2015.06.010.

Develey, P.F., Stouffer, P.C., 2008. Effects of roads on movements by understory birds in mixed-species flocks in central amazonian Brazil. Conserv. Biol. 15, 1416–1422. https://doi.org/10.1111/j.1523-1739.2001.00170.x.

Eigenbrod, F., Hecnar, S.J., Fahrig, L., 2008. Accessible habitat: an improved measure of the effects of habitat loss and roads on wildlife populations. Landsc. Ecol. 23, 159–168. https://doi.org/10.1007/s10980-007-9174-7.

Gaston, K.J., Fuller, R.A., 2008. Commonness, population depletion and conservation biology. Trends Ecol. Evol. 23, 14–19. https://doi.org/10.1016/j.tree.2007.11.001.

Grilo, C., Ascensão, F., Santos-Reis, M., Bissonette, J.A., 2011. Do well-connected landscapes promote road-related mortality? Eur. J. Wildl. Res. 57, 707–716. https://doi.org/10.1007/s10344-010-0478-6.

Holderegger, R., Di Giulio, M., 2010. The genetic effects of roads: a review of empirical evidence. Basic Appl. Ecol. 11, 522–531.

Howe, E.J., Buckland, S.T., Després-Einspenner, M.-L., Kühl, H.S., 2017. Distance sampling with camera traps. Methods in Ecology and Evolution 8, 1558–1565. https://doi.org/10.1111/2041-210X.12790.

Ibisch, P.L., Hoffmann, M.T., Kreft, S., Pe'er, G., Kati, V., Biber-Freudenberger, L., DellaSala, D.A., Vale, M.M., Hobson, P.R., Selva, N., 2016. A global map of roadless areas and their conservation status. Science 354, 1423–1427. https://doi.org/10.1126/science.aaf7166.

Ito, T.Y., Lhagvasuren, B., Tsunekawa, A., Shinoda, M., Takatsuki, S., Buuveibaatar, B., Chimeddorj, B., 2013. Fragmentation of the habitat of wild ungulates by anthropogenic barriers in Mongolia. PLoS One 8 e56995.

Jakes, A.F., Jones, P.F., Paige, L.C., Seidler, R.G., Huijser, M.P., 2018. A fence runs through it: a call for greater attention to the influence of fences on wildlife and ecosystems. Biol. Conserv. 227, 310–318. https://doi.org/10.1016/j.biocon.2018.09.026.

Jones, M.E., 2000. Road upgrade, road mortality and remedial measures: impacts on a population of eastern quolls and Tasmanian devils. Wildl. Res. 27, 289–296. https://doi.org/10.1071/WR98069.

Kays, R., Crofoot, M.C., Jetz, W., Wikelski, M., 2015. Terrestrial animal tracking as an eye on life and planet. Science 348, aaa2478. https://doi.org/10.1126/science.aaa2478.

Kornilev, Y.V., Price, S.J., Dorcas, M.E., 2006. Between a rock and hard place: responses of Eastern Box Turtles (Terrapene carolina) when trapped between railroad tracks. Herpetol. Rev. 37, 145–148.

Kunz, T.H., Arnett, E.B., Erickson, W.P., Hoar, A.R., Johnson, G.D., Larkin, R.P., Strickland, M.D., Thresher, R.W., Turtle, M.D., 2007. Ecological impacts of wind energy development on bats: questions, research needs, and hypotheses. Front. Ecol. Environ. https://doi.org/10.1890/1540-9295(2007)5[315:EIOWED]2.0.CO;2.

Lister, N.M., Brocki, M., Ament, R., 2015. Integrated adaptive design for wildlife movement under climate change. Front. Ecol. Environ. 13, 493–502. https://doi.org/10.1890/150080.

Loss, S.R., Will, T., Marra, P.P., 2014a. Estimation of bird-vehicle collision mortality on U.S. roads. J. Wildl. Manag. 78, 763–771. https://doi.org/10.1002/jwmg.721.

Loss, S.R., Will, T., Marra, P.P., 2014b. Refining estimates of bird collision and electrocution mortality at power lines in the United States. PLoS One 9 e101565. https://doi.org/10.1371/journal.pone.0101565.

Loss, S.R., Will, T., Marra, P.P., 2013. Estimates of bird collision mortality at wind facilities in the contiguous United States. Biol. Conserv. 168, 201–209.

Lunney, D., O'Neill, L., Matthews, A., Sherwin, W.B., 2002. Modelling mammalian extinction and forecasting recovery: Koalas at Iluka (NSW, Australia). Biol. Conserv. 106, 101–113. https://doi.org/10.1016/S0006-3207(01)00233-6.

Marsh, D.M., Milam, G.S., Gorham, N.P., Beckman, N.G., 2005. Forest roads as partial barriers to terrestrial salamander movement. Conserv. Biol. 19, 2004–2008. https://doi.org/10.1111/j.1523-1739.2005.00238.x.

Osborne, P.E., 2005. Key issues in assessing the feasibility of reintroducing the great bustard Otis tarda to Britain. Oryx 39, 22–29. https://doi.org/10.1017/S0030605305000050.

Peris, S., Morales, J., 2004. Use of passages across a canal by wild mammals and related mortality. Eur. J. Wildl. Res. 50, 67–72. https://doi.org/10.1007/s10344-004-0045-0.

Pinto, M., Rocha, P., Moreira, F., 2005. Long-term trends in great bustard (Otis tarda) populations in Portugal suggest concentration in single high quality area. Biol. Conserv. 124, 415–423. https://doi.org/10.1016/j.biocon.2005.01.047.

Ponce, C., Alonso, J.C., Argandoña, G., García Fernández, A., Carrasco, M., 2010. Carcass removal by scavengers and search accuracy affect bird mortality estimates at power lines. Anim. Conserv. 13, 603–612.

Roedenbeck, I.A., Fahrig, L., Findlay, C.S., Houlahan, J.E., Jaeger, J.A., Klar, N., Kramer-Schadt, S., Van der Grift, E.A., 2007. The Rauischholzhausen agenda for road ecology. Ecol. Soc. 12.

Santos, R., Santos, S.M., Santos-Reis, M., Picanço de Figueiredo, A., Bager, A., Aguiar, L.M.S., Ascensão, F., 2016. Carcass persistence and detectability: reducing the uncertainty surrounding wildlife-vehicle collision surveys. PLoS One 11 e0165608. https://doi.org/10.1371/journal.pone.0165608.

Santos, R.A., Ascensão, F., Ribeiro, M.L., Bager, A., Santos-Reis, M., Aguiar, L., 2017. Assessing the consistency of hotspot and hot-moment patterns of wildlife road mortality over time. Perspectives in Ecology and Conservation 15, 56–60. https://doi.org/10.1016/j.pecon.2017.03.003.

Sergio, F., Marchesi, L., Pedrini, P., Ferrer, M., Penteriani, V., 2004. Electrocution alters the distribution and density of a top predator, the eagle owl Bubo bubo. J. Appl. Ecol. 41, 836–845. https://doi.org/10.1111/j.0021-8901.2004.00946.x.

Shaw, J.M., Jenkins, A.R., Smallie, J.J., Ryan, P.G., 2010. Modelling power-line collision risk for the Blue Crane Anthropoides paradiseus in South Africa. Ibis 152, 590–599. https://doi.org/10.1111/j.1474-919X.2010.01039.x.

Taylor, P.D., Fahrig, L., Henein, K., Merriam, G., 1993. Connectivity is a vital element of landscape structure. Oikos 68, 571–573. https://doi.org/10.2307/3544927.

Teixeira, F.Z., Coelho, A.V.P., Esperandio, I.B., Kindel, A., 2013. Vertebrate road mortality estimates: effects of sampling methods and carcass removal. Biol. Conserv. 157, 317–323. https://doi.org/10.1016/j.biocon.2012.09.006.

Teixeira, F.Z., Kindel, A., Hartz, S.M., Mitchell, S., Fahrig, L., 2017. When road-kill hotspots do not indicate the best sites for road-kill mitigation. J. Appl. Ecol. 54, 1544–1551. https://doi.org/10.1111/1365-2664.12870.

Tyler, N., Stokkan, K.A., Hogg, C., Nellemann, C., Vistnes, A.I., Jeffery, G., 2014. Ultraviolet vision and avoidance of power lines in birds and mammals. Conserv. Biol. https://doi.org/10.1111/cobi.12262.