Chapter 28

THE IMPACTS OF ROADS AND TRAFFIC ON TERRESTRIAL ANIMAL POPULATIONS

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SUMMARY

There is growing evidence that roads and traffic reduce populations of many species and efforts to mitigate road effects are now common. To maximise understanding of road impacts and for conservation of particular species, we need to know how roads affect the viability of a group of individuals of the species rather than a single individual. Roads and traffic affect wildlife populations in three major ways, by (i) increasing mortality, (ii) decreasing habitat amount and quality and (iii) fragmenting populations into smaller sub-populations which are more vulnerable to local extinction. To ensure mitigation is effective, we need to identify the species most affected, and the cause(s) of the effects, so that appropriate mitigation can be tailored to those species.

28.1 Mammals: Larger, more mobile species with lower reproductive rates are more susceptible to road mortality, and species that avoid roads from a distance due to traffic-related disturbance are susceptible to habitat fragmentation, loss and degradation.

28.2 Birds: Species that have large territories and possibly species that are low flying, ground dwelling and/or heavy relative to their wing size are more susceptible to road mortality.

28.3 Amphibians and reptiles: All species, regardless of life history traits, are prone to negative road effects as they are particularly susceptible to road mortality and habitat fragmentation by roads.

28.4 A species response to roads and traffic will vary depending on its conservation status, geographical location, habitat preferences, road type and/or traffic volume.

28.5 There are still many species for which we do not know the population-level effects of roads. To ensure mitigation will be effective for as many species as possible, research is needed on the effects of roads on a broader range of species.

This chapter provides a high-level overview of the population-level effects of roads on animals using the available data from 75 studies. For more detailed information on specific species groups, please refer to Chapters 29–45.

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INTRODUCTION

There are many studies on the effects of roads on animal movement and mortality, neither of which allows for strong inference about the impacts of roads on population persistence; for example, it is possible that increased reproduction rates counterbalance losses caused by road mortality (Roedenbeck et al. 2007). For conservation of a particular species, we need to know how roads affect the viability of a group of individuals (i.e. the population) rather than a single individual. The main question is therefore: can roads and/or traffic reduce or even eliminate a population, and how? Roads and traffic affect wildlife populations in three major ways, by (i) increasing mortality, (ii) decreasing habitat amount and quality and (iii) fragmenting populations into smaller sub-populations that each are more vulnerable to local extinction than a large population.

The vulnerability of a species to roads and/or traffic is influenced by its ecological traits and behavioural responses (Table 28.1). Important ecological traits are its reproductive rate (a higher reproductive rate allows populations to recover from road mortality) and its mobility (a more mobile species will encounter roads more often than species that are more sedentary). Four types of behaviour influence whether roads or traffic affects animal populations: (i) avoidance of the road surface; (ii) avoidance of traffic disturbance (noise, lights, chemical emissions); (iii) vehicle avoidance (the ability to move out of the path of an oncoming vehicle); and (iv) attraction to roads (Fig. 28.1). Species that avoid the road surface are less likely to be killed on roads because they rarely attempt to cross it, but they may have trouble accessing important habitats or resources on the other side of the road. Similarly, animals that avoid traffic disturbance are less susceptible to road mortality, but their populations may be fragmented into smaller, partially isolated populations that may be more vulnerable to extinction. Avoidance of traffic disturbance also reduces the amount of habitat since the area near roads becomes unsuitable (i.e. road effect zone; Lesson 1.2). Species that can move out of the path of an oncoming vehicle should be less susceptible to road mortality and may be able to cross the road when traffic volumes are not too high. Lastly, some species can be attracted to roads for a resource such as carrion (e.g. some birds) and nesting sites (e.g. some turtles) or to bask (e.g. some snakes) which can make them vulnerable to road mortality (Chapters 32 and 33).

The insights in this chapter are based on a formal review of 75 studies published during 1979–early 2011 that measured the relationship between roads and/or traffic and population size of a species. Studies were predominantly in North America (49 studies) or Europe (19), but a few were from Oceania (3), Africa (2), and Asia (2). For each study, the raw data were either provided in the paper (e.g. from graphs or figures) or they were provided directly by the authors. To determine whether a species was negatively or positively affected or unaffected (neutral effect) by roads,

Table 28.1 Characteristics that can affect a species vulnerability to the major impacts of roads.

Characteristics that affect a species vulnerability to road effects	Effects of roads and/or traffic: Road mortality	Habitat loss/reduced habitat quality	Habitat fragmentation/reduced connectivity
Low reproductive rate	x	x	x
Young age at sexual maturity	x	x	x
Long generation time (lifespan)	x	x	x
High intrinsic mobility	x		
Large area requirements/low natural density	x	x	x
Large body size	x	x	x
Multiple resource needs	x		x
Attraction to roads	x		
Road surface avoidance			x
Traffic disturbance avoidance		x	x
No road or traffic disturbance avoidance	x		

Source: Adapted from Forman et al. (2003).

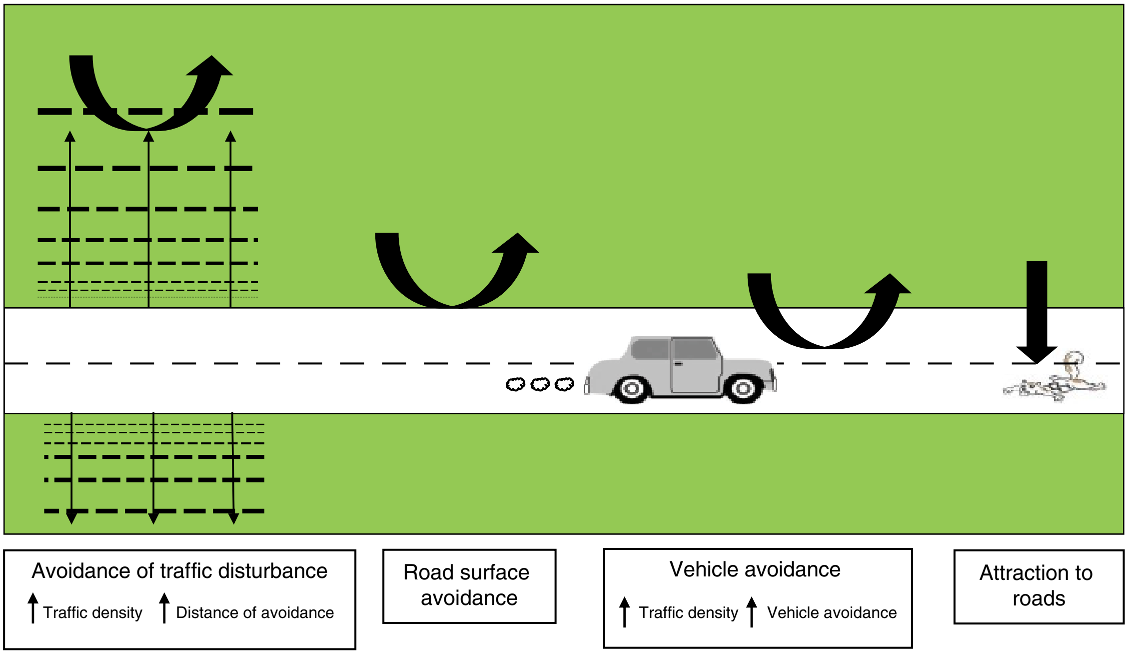

Figure 28.1 Illustration of species behavioural responses to roads and traffic. 'Avoidance of traffic disturbance' is avoidance of roads from a distance due to traffic disturbance (e.g. lights, noise, chemical emissions). As traffic density increases, the distance at which a species avoids the road (represented as black dashed lines) increases resulting in more habitat effectively lost to a species (strength of effect represented by thickness of dashed lines). 'Road surface avoidance' is a short distance avoidance of the road surface itself due to a lack of cover and/or to the character of embankment and pavement which is different from natural habitat. 'Vehicle avoidance' is the avoidance of oncoming vehicles. 'Attraction to roads' is when animals are attracted to a road for a resource (e.g. for food, a nesting site, a mate or thermoregulation). Source: Adapted from Jaeger et al. (2005).

the data from each study were converted into a common measure, the Pearson correlation coefficient r, a measure of the strength of the relationship between roads and an animal's population abundance. The coefficient, r, ranges from -1.00 (largest negative effect) through 0 (no effect) to $+1.00$ (largest positive effect). To determine species traits that make them prone to negative road and/or traffic effects, we considered traits that are related to population abundance: reproductive rate and/or age at sexual maturity, species mobility and body size. Full details of the methods are in Rytwinski and Fahrig (2012). We limit the discussion here to four groups of vertebrates – mammals, birds, amphibians and reptiles that spend at least part of their life cycle on land. Invertebrates were not included in this discussion because there were too few population-level studies, but see Chapters 29 and 30 for more details on this group.

When reading this chapter, two points are important. First, when more than one study was conducted on a particular species, we determined the average direction and size of the road effect. While this provides an indication of the overall effect of roads on the species, studies conducted in different locations or habitats may actually measure different road effects on a species (Lesson 28.4). Second, we present information based only on studies that have measured the effect of roads on at least one population. Many other species may be affected by roads but have not yet been studied (Lesson 28.5).

The aims of this chapter are to identify (i) the animals whose populations are most vulnerable to road impacts, (ii) species traits and behavioural responses to roads that make animals vulnerable to road impacts and (iii) the likely causes of those impacts, so that appropriate road mitigation measures can be identified. For mitigation to be effective, the cause of the impact must be specifically addressed. For example, if a species is mainly affected by road mortality, mitigation should be directed towards preventing animals from moving onto roads. In this case, installing wildlife crossing structures would not adequately address the main issue of road mortality, unless fencing was also installed.

LESSONS

28.1 Mammals: Larger, more mobile species with lower reproductive rates are more susceptible to road mortality, and species that avoid roads from a distance due to traffic-related disturbance are susceptible to habitat fragmentation, loss and degradation

Population-level effects

A total of 34 studies from 12 countries that included 84 mammal species were reviewed. From these, 127 records of road and/or traffic effects were extracted. Most studies of mammals at the population level to date have been conducted on three orders: (i) rodents (27 species), (ii) hoofed mammals (more specifically even-toed ungulates) (16 species) and (iii) carnivores (24 species) (Fig. 28.2). On average, rodent and hoofed mammal populations increase, and carnivore populations decrease in response to roads (Fig. 28.2).

Of the rodents studied, only a few species are negatively affected by roads compared to a much higher number that are either positively affected or unaffected (Fig. 28.3A(i)). Species showing negative population-level effects are mid-sized species of arboreal squirrels (grey squirrel, Lord Derby's scaly-tailed squirrel, Beecroft's scaly-tailed squirrel) and the California vole. Rodents showing positive or neutral

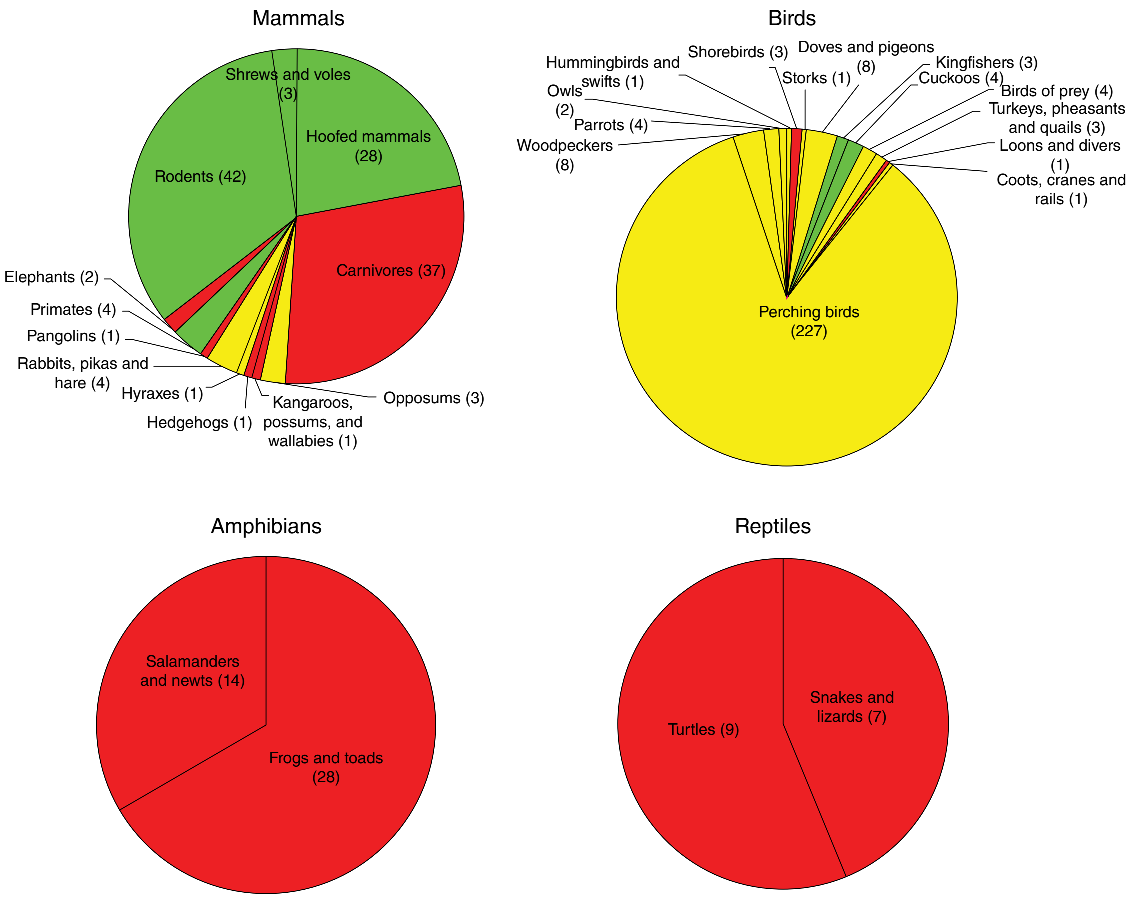

Figure 28.2 Proportion of the total number of road effects extracted for review for the various animal orders for each class. Numbers in brackets correspond to the number of road effects extracted for each animal order out of a total of 127 for mammals, 270 for birds, 42 for amphibians and 16 for reptiles. Colours correspond to the direction in which populations are responding on average to road impacts: red, negatively affected (population abundance decreasing); yellow, unaffected (no change in population abundance); and green, positively affected (population abundance increasing).

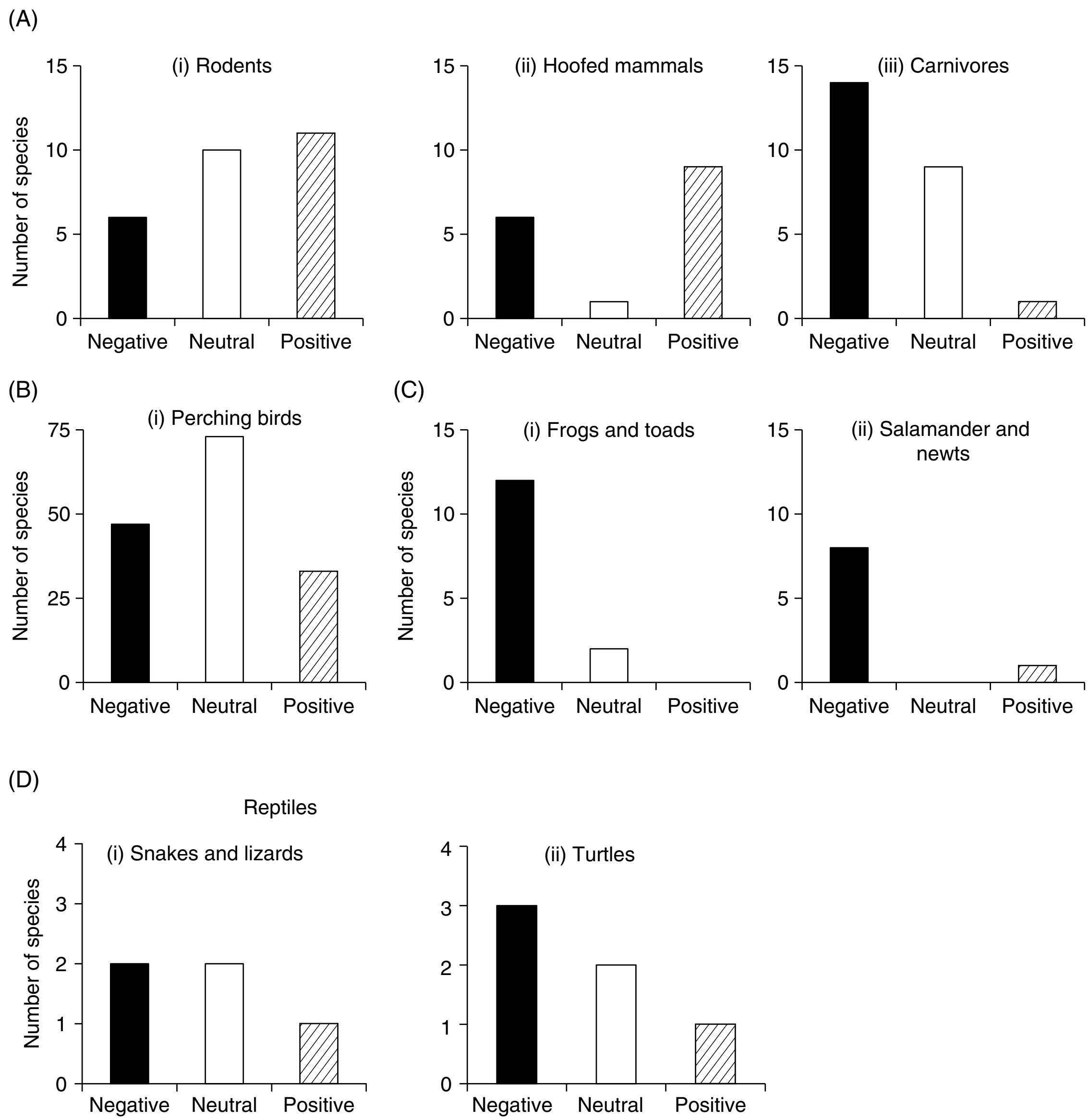

Figure 28.3 The number of species within each animal order showing on average negative, neutral, or positive effects of roads on their population abundance for (A) mammals, (B) birds, (C) amphibians and (D) reptiles.

effects of roads are typically smaller: for example, white-footed mouse and least chipmunk.

For the hoofed mammals, the number of studied species showing positive population-level effects of roads is nearly double the number showing negative effects (Fig. 28.3A(ii)). Species showing negative effects include North American elk, wild boar, European roe deer, woodland caribou and mule deer. Species showing positive effects include white-tailed deer, moose, Peter's duiker and yellow-backed duiker. It has been suggested that the positive effects of roads on large herbivores such as white-tailed deer (and indeed small mammals as well) may be due to predation release, as populations of many of their main predators are reduced in areas of high road density (Munro et al. 2012).

Overall, carnivores are the most negatively affected mammalian order (Fig. 28.3A(iii)). Examples include members of the bear family (sloth bear, grizzly bear and black bear), the mustelid family (Eurasian badger, fisher and wolverine) and the felid family (leopard, Iberian lynx and Eurasian lynx). Of those studied, the only carnivore showing a positive effect of roads is the Siberian weasel, likely due to its higher reproductive rate and smaller home rage size compared to larger-sized carnivores.

Species traits

Larger, more mobile mammals with lower reproductive rates are more susceptible to negative road effects on their populations than smaller, less mobile species with higher reproductive rates. We hypothesise that species with lower reproductive rates are less able to recover from population declines due to road mortality. Species that frequently move long distances are likely more affected by road mortality, because they interact with roads more often than less mobile species. For the same reasons, species with larger territories or home ranges are also more susceptible to road effects than those with smaller territories or home ranges. This means that, in general, larger species are more affected than smaller species because they generally have lower reproductive rates and are more mobile than smaller species (Chapter 39).

There can however be exceptions to the aforementioned generalities. Hypothetically, if a species is locally abundant but of limited geographic range and/or dispersal capability, the population may be vulnerable to road impacts despite it having a high reproductive rate and/or being less mobile.

Behavioural responses to roads and/or traffic

Anecdotal observations of an animal reacting to a road or vehicle are common. However, there are actually very few quantitative studies documenting such behaviours. A scarcity of animals in areas of high road density is sometimes assumed to indicate road avoidance, but this assumption may not be valid because such a scarcity could also be caused by mortality. Even documenting movement paths of animals near roads cannot tell us whether the animal is avoiding the road itself or the traffic on it, unless animals only cross the road when traffic volume is very low.

From the available studies, populations of mammals that avoid roads from a distance due to traffic disturbance are more negatively affected by roads than are populations of species that avoid the road surface itself. While both behaviours can make a species more vulnerable to habitat fragmentation, avoidance of traffic-related disturbance also reduces the amount of habitat since the area near roads becomes unsuitable. Species that avoid roads from a distance include woodland caribou, North American elk, moose and grizzly bear. With the exception of moose, all of these species also show negative population-level effects of roads. Species that have been shown to avoid the road surface include white-footed mouse and eastern chipmunk, and their populations are either positively affected or unaffected by roads.

28.2 Birds: Species that have large territories and possibly species that are low flying, ground dwelling and/or heavy relative to their wing size are more susceptible to road mortality

Population-level effects

A total of 16 studies from 8 countries that included 194 bird species were reviewed. From these, 270 records of road and/or traffic effects were extracted. Most studies of the effects of roads on bird populations have been on perching birds, that is, passerines (153 of 194 species) (Fig. 28.2). While some species within this group show negative population effects of roads, there is no strong overall effect (Fig. 28.2).

Of the perching birds studied, examples of those showing negative population effects include species from the chats and old world flycatchers (northern wheatear and European robin), sandpipers (common redshank), wrens (winter wren and sedge wren) and Australian treecreepers (brown treecreeper and white-throated treecreeper). Species showing neutral or positive effects are primarily from the buntings, American sparrows (song sparrow and rock bunting) and new world warblers (black-throated blue warbler and Nashville warbler).

Species traits

In general, more mobile birds (i.e. species with larger territories) are more susceptible to road effects than are less mobile species. While this is the only species trait found to explain variation in bird population-level effects of roads in our literature review, researchers have suggested other potentially important traits that were not included in our analyses. For example, ground-dwelling birds have been suggested to be at greater risk of wildlife-vehicle collisions (WVC) because they spend longer time on the road surface and in low flight (Jacobson 2005). Furthermore, birds that are heavy relative to their wing size (e.g. female owls) or have a low take-off trajectory may also be more vulnerable to WVC (Kociolek & Clevenger 2011). Species that need to move between different habitat types (e.g. some woodland birds and wintering water birds) are likely more sensitive to road impacts (Chapter 33).

Behavioural responses to roads and/or traffic

There are very few studies documenting behavioural responses to roads and/or traffic in birds. Road attraction behaviour has been shown in two species (common raven and black kite). For both species, populations have been found to be unaffected by roads, even though mortality does occur (Palomino & Carrascale 2007). Although there are no quantitative studies of vehicle avoidance in these species, if they do show vehicle avoidance and if they benefit from the carrion resource on roads, a positive effect of this food resource on reproduction could balance or even outweigh negative effects of road mortality, the net effect being the observed neutral road effects on their populations.

Many authors have either argued or assumed that traffic noise is the main cause of negative road effects on bird populations. Traffic noise could interfere with the ability to communicate by song which could make it hard for some species of birds to attract mates and/or defend territories (Rheindt 2003). Traffic noise could also distract individuals making them more vulnerable to predation. These conclusions are based mainly on observations of both lower bird occurrence and higher traffic noise in locations closer to roads (Chapter 19). However, in addition to traffic noise, road mortality should be higher closer to roads, so it is not clear whether noise or mortality (or both) is the real cause of the negative effects on bird populations. Distinguishing these is important for designing appropriate mitigation (Summers et al. 2011). The finding that more mobile birds are more prone to road effects than less mobile species indirectly supports the mortality hypothesis over the noise disturbance hypothesis. In addition, some of the studies of road effects on birds were designed such that the effects of distance from the road and distance from habitat edge are confounded, which means that apparent road effects could be partly or even mainly due to negative edge effects (Delgado García et al. 2007; but see Summers et al. 2011).

28.3 Amphibians and reptiles: All species, regardless of life history traits, are prone to negative road effects as they are particularly susceptible to road mortality and habitat fragmentation by roads

Population-level effects

For amphibians, 16 studies from 6 countries that included a total of 23 species were reviewed. From these, 42 records of road and/or traffic effects were extracted. On average, roads and traffic reduce populations of frogs and toads and salamanders (Fig. 28.2). For reptiles, 9 studies from 3 countries that included a total of 11 species were reviewed, from which 16 records of road effects were extracted. On average, populations of turtles and snakes and lizards are negatively affected by roads (Fig. 28.2).

Although amphibians and reptiles have significantly more species at risk than either mammals or birds (IUCN 2010), there are relatively few studies of the effects of roads on their populations. Those that do exist suggest that amphibians are in general negatively affected by roads, with only one species showing a positive effect (northern two-lined salamander) (Fig. 28.3C(i) and (ii)). Frogs showing negative population-level effects include the spring peeper, European tree frog, northern leopard frog, wood frog and common spadefoot toad. Salamanders showing negative effects include the tiger salamander, blue-spotted salamander, red-backed salamander, seal salamander and eastern newt.

There are only 11 reptile species for which the population-level effects of roads have been evaluated. About equal numbers of snake species show negative and neutral effects of roads, and one species showed a weak positive effect (eastern diamondback rattlesnake) (Fig. 28.3D(i)). Snakes showing negative population-level effects include the lava lizard and timber rattlesnake, and those showing neutral effects include eastern massasauga rattlesnake and eastern hog-nosed snake.

Population-level effects of roads on turtles are mixed with three species showing negative effects (desert tortoise, wood turtle and spotted turtle), two showing neutral effects (common snapping turtle and common musk turtle) and one showing a positive effect (painted turtle) (Fig. 28.3D(ii)).

Species traits

In general, populations of amphibian species with lower reproductive rates are more susceptible to negative road effects than species with higher reproductive rates.

Many reptiles are long-lived with high natural year-to-year survival of the adults, and many make long movements over land searching for nests or mates. These characteristics along with their slow movements across roads make reptile populations particularly vulnerable to road mortality. There may be more negative effects of roads on reptiles than suggested by studies to date because it is difficult to estimate reptile population sizes, which would make it hard to detect effects (Chapter 32). Also, for species that nest along roads (e.g. painted turtles), the negative effect of road mortality may be compensated by lower rates of nest predation (Langen 2009).

Species that need to move among different habitats are also particularly susceptible to road mortality and landscape fragmentation by roads. For example, many frogs and salamanders need to move among aquatic breeding habitats, upland feeding habitats and specialised overwintering habitats to complete a life cycle. When these habitats are not adjacent, amphibians must move long distances, sometimes several kilometres, to find them. At high road density, the chance of all these habitats occurring within an area absent of roads is unlikely. In some cases, such as when roads run adjacent to a river or stream, all animals in the population must cross roads to reach other habitats, resulting in a very high mortality rate (Chapter 31).

Road mortality also affects amphibian and reptile populations indirectly by reducing reproductive rate. Reproductive rate of amphibians and reptiles increases with age because larger animals have more eggs and they keep growing as they age. Roadkill results in a shift in age within the population towards younger individuals, which are smaller, and this reduces the overall reproductive rate of the population (Karraker & Gibbs 2011).

Behavioural responses to roads and/or traffic

There are not many studies of amphibian and reptile behavioural responses to roads. Three snakes, the timber rattlesnake, the eastern hog-nosed snake and the eastern massasauga rattlesnake, avoid the road surface (Andrews & Gibbons 2005), and of these three species, only the timber rattlesnake showed a negative population-level effect of roads. There is one study of the behavioural response of frogs to roads; the northern leopard frog showed no behavioural avoidance of roads or traffic (Bouchard et al. 2009), which probably explains its negative population-level response to roads, likely due to abundant road mortality.

28.4 A species response to roads and traffic will vary depending on its conservation status, geographical location, habitat preferences, road type and/or traffic volume

In our review, we determined the average direction and size of the road effect when more than one study was conducted on a particular species. While this provides an indication of the overall effect of roads on a particular species, the individual studies may have been conducted in different locations or habitat types, for example, Florida versus California, United States, using different road measures, for example, road density versus traffic density, or road types, for example, highways versus gravel roads, which may result in different road effects on population abundance. For example, grey wolves respond negatively to increasing road density in northern Wisconsin and upper Michigan, United States (Mladenoff et al. 1995), but positively in the boreal forest of northern Ontario, Canada (Bowman et al. 2010). On average, the wolf response is neutral, but this hides these different positive and negative effects. The regional difference could be because most roads in northern Ontario are lightly used gravel logging roads, whereas in northern Wisconsin and Michigan, they are paved roads with higher traffic volumes. Therefore, effects of roads may be context or location dependent so extrapolation of road effects for a species from one region to another should be carefully scrutinised.

Road effects may also be dependent on the conservation status of the species or its local population. For example, it is possible that a species with traits that would normally make it resilient to road effects may already be so depleted in an area from other causes that a new road, even with relatively low rates of mortality or reduced habitat connectivity, may be sufficient to cause it to decline further, possibly to local extinction.

28.5 There are still many species for which we do not know the population-level effects of roads. To ensure mitigation will be effective for as many species as possible, research is needed on the effects of roads on a broader range of species

There are large biases towards studies on certain groups of mammals and birds, leaving gaps in knowledge on population-level effects of roads for many species and species groups. Most studied mammals belong to either the rodent, hoofed mammal or carnivore orders (i.e. 67 of the 84 studied species), highlighting the need for more population-level studies for other orders. Furthermore, the majority of population-level bird studies have been conducted on perching birds (passerines) (153 of 194 species studied). On average, there was no strong overall effect of roads found for this group. If all perching birds were found to have a trait that makes them tolerant to road effects, this could explain this lack of effect, suggesting that more studies on a wider range of bird orders are needed. Some of the empirical studies reporting road effects on birds were designed such that the effects of distance from the road and distance from habitat edge are confounded, which means that apparent road effects could be partly or even mainly because of habitat edge effects on birds (but see Summers et al. 2011). With a combined species total of 34, amphibians and reptiles were the least represented animal groups in this review, suggesting more population-level studies are needed.

To better facilitate future reviews such as this one or to estimate potential effects for new road projects, we have the following recommendations. First, when reporting an effect of roads and/or traffic on a species population abundance, authors should include (i) the test statistic for the effect (e.g. F or r^2) and/or summary statistics (e.g. mean and variance) from which an effect size can be calculated and (ii) the sample size (or the P value of the test if a test statistic was reported). The number of studies that could be included in our review was often limited by the lack of statistical information provided. Second, authors should provide a brief description of the ecology of the species of interest, including information on species traits for the geographical location of the study, along with references, as this information is often lacking or difficult to obtain for researchers living in different regions. Third, authors should include maps with a scale or provide GPS coordinates of study locations/sites to allow the potential of further analyses of landscape variables or evaluation of spatial independence of study sites.

CONCLUSIONS

From the available literature, there is evidence that road mitigation should be considered for wide-ranging large mammals with low reproductive rates; birds with larger territories; possibly birds that are low flying, ground dwelling and/or heavy relative to their wing size; all amphibians and reptiles (due to road mortality); and species that do not avoid roads or are known to be disturbed by traffic. For species that are mainly affected by roads through road mortality, mitigation should focus on preventing animals from moving onto roads (e.g. fences; Chapter 20). For species that are disturbed by traffic, road effects can be mitigated by measures aimed at reducing road and traffic density in the landscape (e.g. by closing some roads (Chapter 3) or increasing the capacity of roads outside important wildlife areas). In addition, engineering solutions to reduce traffic noise (e.g. changes to pavement or tyres) could partially mitigate the disturbance effects. For species that are mainly affected by roads through habitat fragmentation, mitigation should focus on improving habitat connectivity by installing wildlife crossing structures (Chapter 21).

When there is an endangered species present or when a population is declining or at risk of local extinction due to other disturbances or modifications to the environment, roads should be mitigated even if they are not the main reason for the species' endangerment or decline. Even if the rate of road mortality on such a species is low, any additional mortality or reduced connectivity can drive it to extinction. Furthermore, species responses to roads are sometimes context (e.g. habitat type studied, road/traffic measure used and/or road type studied) or location dependent, so road impacts on species for a given location of interest should be considered carefully before new roads are constructed or modified.

While our review included 312 species and 455 data sets on population-level effects of roads, large biases towards studies on certain groups of mammals (i.e. rodents, hoofed mammals and carnivores) and birds (i.e. perching birds) were uncovered, highlighting the need for more population-level studies for other species groups.

ACKNOWLEDGEMENTS

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FURTHER READING

Fahrig and Rytwinski (2009): Provides our preliminary review findings of the effects of roads on animal abundance and examples of some of the common issues associated with road ecology study designs.

Roedenbeck et al. (2007): Based on discussions during the 'Landscape-scale effects of roads and biodiversity' workshop in Germany in 2005, this paper identifies the questions in road ecology of most direct relevance to the decision-making process and then provides suggestions for designing studies that have high inferential strength to address those questions.

Rytwinski and Fahrig (2012): This paper formed the basis of the information provided within this chapter. Further information on the methodology used to carry out the review as well as further discussion on its findings and the actual data itself can be retrieved within this paper and its supporting information.

REFERENCES

Andrews, K. M. and J. W. Gibbons. 2005. How do highways influence snake movement? Behavioral responses to roads and vehicles. Copeia **2005**:772–782.

Bouchard, J., A. T. Ford, F. E. Eigenbrod and L. Fahrig. 2009. Behavioral responses of northern leopard frogs (*Rana pipiens*) to roads and traffic: implications for population persistence. Ecology and Society **14**:23. Available from http://www.ecologyandsociety.org/vol14/iss2/art23/ (accessed 28 September 2014).

Bowman, J., J. C. Ray, A. J. Magoun, D. S. Johnson and F. N. Dawson. 2010. Roads, logging, and the large-mammal community of an eastern Canadian boreal forest. Canadian Journal of Zoology **88**:454–467.

Delgado García, J. D., J. R. Arévalo and J. M. Fernández-Palacios. 2007. Road edge effect on the abundance of the lizard *Gallotia galloti* (*Sauria: Lacertidae*) in two Canary Islands forests. Biodiversity and Conservation **16**:2949–2963.

Fahrig, L. and T. Rytwinski. 2009. Effects of roads on animal abundance: an empirical review and synthesis. Ecology and Society **14**:21. Available from http://www.ecologyandsociety.org/vol14/iss1/art21/ (accessed 28 September 2014).

Forman, R. T. T., D. Sperling, J. A. Bissonette, A. P. Clevenger, C. D. Cutshall, V. H. Dale, L. Fahrig, R. France, C. R. Goldman, K. Heanuem, J. A. Jones, F. J. Swanson, T. Turrentine and T. C. Winter. 2003. Road ecology: science and solutions. Island Press, Washington, DC.

International Union for the Conservation of Nature (IUCN). 2010. IUCN red list of threatened species. IUCN, Gland, Switzerland. Available from http://www.iucn.org (accessed 28 September 2014).

Jacobson, S. J. 2005. Mitigation measures for highway-caused impacts to birds. General technical report PSW-GTR-191. USDA Forest Service, Washington, DC.

Jaeger, J. A. G., J. Bowman, J. Brennan, L. Fahrig, D. Bert, J. Bouchard, N. Charbonneau, K. Frank, B. Gruber and K. Tluk von Toschanowitz. 2005. Predicting when animal populations are at risk from roads: an interactive model of road avoidance behavior. Ecological Modeling **185**:329–348.

Karraker, N. E. and J. P. Gibbs. 2011. Contrasting road effect signals in reproduction of long- versus short-lived amphibians. Hydrobiologia **66**:213–218.

Kociolek, A. V. and A. P. Clevenger. 2011. Effects of paved roads on birds: a literature review and recommendations for the Yellowstone to Yukon ecoregion. Technical report #8. Yellowstone to Yukon Conservation Initiative, Canmore, Alberta. Available from http://y2y.net/files/979-y2y-technical-report-8-effects-of-paved-roads-on-birds.pdf (accessed 28 September 2014).

Langen, T. A. 2009. Design and testing of prototype barriers and tunnels to reduce the impact of roads on turtle survival and reproductive success. Final report MOU AM05405. New York State Department of Environmental Conservation US Fish & Wildlife Service, Albany, NY.

Mladenoff, D. J., T. A. Sickley, R. G. Haight and A. P. Wydeven. 1995. A regional landscape analysis and prediction of favourable gray wolf habitat in the northern Great-Lakes region. Conservation Biology **9**:279–294.

Munro, K. G., J. Bowman and L. Fahrig. 2012. Effect of paved road density on abundance of white-tailed deer. Wildlife Research **39**:478–487.

Palomino, D. and L. M. Carrascale. 2007. Threshold distances to nearby cities and roads influence the bird community of a mosaic landscape. Biological Conservation **140**:100–109.

Rheindt, F. E. 2003. The impact of roads on birds: does song frequency play a role in determining susceptibility to noise pollution? Journal für Ornithologie **144**:295–306.

Roedenbeck, I. A., L. Fahrig, C. S. Findlay, J. E. Houlahan, J. A. G. Jaeger, N. Klar, S. Kramer-Schadt and E. A. van der Grift. 2007. The Rauischholzhausen agenda for road ecology. Ecology and Society **12**:11–32.

Rytwinski, T. and L. Fahrig. 2012. Do species life history traits explain population responses to roads? A meta-analysis. Biological Conservation **147**:87–98.

Summers, P. D., G. M. Cunnington and L. Fahrig. 2011. Are negative effects of roads on breeding birds caused by traffic noise? Journal of Applied Ecology **48**:1527–1534.