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13

Impacts of Landscape Transformation by Roads

LAURIE W. CARR, LENORE FAHRIG, AND SHEALAGH E. POPE

13.1 Introduction

The transformation of landscapes by roads has spread rapidly with little consideration of the ecological consequences. Between 1986 and 1994, the number of vehicles increased 18%, to over 6 billion world-wide (United Nations 1997). In this chapter, we outline the ecological impacts of roads on biological conservation, from a landscape ecology perspective. In Section 13.2 we outline the relevant landscape ecological concepts, in Section 13.3 we review measures to compensate for negative impacts of roads on wildlife, and in Section 13.4 we outline principles for successful mitigation of landscape-level road effects. Finally, in Sections 13.5 and 13.6, we discuss existing knowledge gaps and suggest research approaches for filling these gaps.

13.2 Concepts, Principles, and Emerging Ideas

Landscape composition, configuration, and connectivity are key descriptors of landscape structure that determine the influence of the landscape on population persistence (Dunning et al. 1992; Taylor et al. 1993). *Composition* is the number and extent of different landscape elements (e.g., habitat types) in a landscape. *Configuration* describes the spatial arrangement of landscape elements, and *connectivity* is the degree to which the landscape facilitates animal movement (Taylor et al. 1993).

13.2.1 Road Effects on Landscape Composition

Roads affect landscape composition through loss of habitat, habitat introduction, and changes in habitat quality. Road construction results in conversion of existing habitats to pavement and road verges. Roads through wooded areas also increase the amount of forest edge, resulting in additional loss of habitat for forest interior species (Ranney et al. 1981). Road construction also can result in the indirect destruction of surrounding habitat through siltation of streams and drying of wetlands,

due to interrupted water flow. The loss of habitat to roads is far from inconsequential. For example, Adams and Geis (1983) estimated that the 6.3 million km of roads and their associated rights-of-way occupied 8.1 million ha in the United States.

Roads also change landscape composition by introducing novel "habitats." Pavement affords resources to few species (thermoregulation for ectotherms and roadkill as a food source being notable exceptions) and, therefore, barely deserves the moniker "habitat." However, vegetated verges and medians provide resources such as forage, shelter, and nest sites to many species (Bennett 1991). Roadside habitat is often characterized by grassland species, generalist species, disturbance-tolerant species, and exotic species (Adams and Geis 1983; Forman and Alexander 1998).

In addition to habitat loss and introduction, roads alter habitat quality through a direct increase in wildlife mortality (Forman and Alexander 1998). For example, during a two-year period, 32,000 amphibians, reptiles, birds, and mammals were found as roadkill along the 3.6-km Long Point Causeway adjacent to Big Creek Wetland, Lake Erie, Canada (Ashley and Robinson 1996). Ehmann and Cogger (1985) estimated that 5.48 million reptiles and frogs are killed in Australia each year by road traffic. The amount of traffic mortality is influenced by traffic volume and movement behavior of the organism (Fahrig et al. 1995; Carr and Fahrig 2001).

Roadside habitats become *ecological traps* when the mortality rate of individuals using this habitat is higher than that of individuals using an alternative habitat. For example, mortality of Florida Scrub-Jays (*Aphelocoma coerulescens*) was almost 100% greater in populations bordering a two-lane country road than it was for populations living away from the road (Mumme 1994, cited in Lidicker and Koenig 1996). Mortality was greatest for immigrants, implying that the roadside habitat was luring birds away from other habitat.

The extent to which road mortality negatively affects local populations depends on the intrinsic growth rate of the organism and the degree to which the killed individuals were surplus to the local population (e.g., juveniles without local territories). Road mortality can be a serious cause of decline for small populations. For example, Harris and Scheck (1991) reported that vehicle collisions were the largest source of mortality for all of Florida's large rare and endangered vertebrates, including panther (*Felis concolor coryi*), black bear (*Ursus americanus floridanus*), key deer (*Odocoileus virginianus clavium*), American crocodile (*Crocodylus acutus*), and Bald Eagle (*Haliaeetus leucocephalus*).

Roads also can create suboptimal habitat through *edge effects* (Murcia 1995). Road edge effects result when adjacent habitat is exposed to road effects such as: runoff of chemicals, particulate matter, and water; noise; and changes in microclimate (Garland and Bradley 1984; Forman 1995; Reijnen 1995). These can have direct biological consequences. For example, an increase in traffic noise is correlated with a decrease in abundance of farmland birds in The Netherlands (Reijnen 1995). Roads also indirectly alter habitat quality by providing human access (e.g., hunting, development) to previously remote areas.

Suboptimal roadside habitat may play a role as *sink habitat* for nonbreeders in *source-sink population dynamics*. Source-sink dynamics occur when a local

source population exceeds the number of breeding sites available, and nonbreeders disperse to a poorer quality sink habitat. In the sink habitat, mean annual reproduction is insufficient to balance mean annual mortality. Immigration from a source population is required to maintain the sink population over the long term. However, sink populations can benefit the overall regional population by temporarily "storing" individuals that can move back into a source habitat, should numbers decline there (Pulliam 1988). If roads convert source habitat to sink habitat, persistence of the regional population can be jeopardized. For example, subordinate and some adult female grizzly bears (*Ursus arctos*) are forced to use roadside habitat in Bow River Valley, Alberta, when adult males and resident females take the highest-quality habitat. Most grizzly bears are unwilling to use habitats with a high human presence (Gibeau and Herrero 1998).

The *road-effect zone* is the area (extending outward from the road) over which the road has significant ecological impacts (Forman and Deblinger 2000). It combines the road effects on habitat loss and habitat quality. The width of the zone depends on the intensity of the road effects and the sensitivity of organisms to them.

13.2.2 Road Effects on Landscape Configuration and Connectivity

Roads affect landscape configuration and connectivity by introducing barriers and corridors into the landscape. These affect landscape processes, including metapopulation dynamics, landscape supplementation, and landscape complementation.

Many species avoid roads in response to the noise, light, altered microclimate, and reduced cover (Bennett 1991). Movement across roads by wood mice, carabid beetles, and lycosid spiders is reduced compared with movement over similar distances in adjacent habitat (Mader 1984; Mader et al. 1990). Oxley et al. (1974) found that road width was the main determinant of reduced crossing by small forest animals. Garland and Bradley (1984) found that desert rodents avoided roads, despite the small difference between the road and the desert environment. Individuals may also be prevented from crossing a road by a physical barrier such as a median barrier, roadside fence, or bank (Andrews 1990).

In addition to the *barrier effect* caused by road avoidance, high road mortality can act as a barrier to movement in the landscape (e.g., van Gelder 1973; Ehmann and Cogger 1985). Road mortality therefore has two effects: (1) it reduces local habitat quality by increasing mortality (Section 13.2.1), and (2) it decreases the rate of movement through the landscape (Figure 13.1).

As barriers, roads can cause *habitat fragmentation*, or the "breaking apart" of habitat, which reduces local population sizes. Smaller populations are at a greater risk of local extinction, due to stochastic demographic, genetic, and environmental events (Wilcox and Murphy 1985). Isolated populations also have a lower chance of survival without the demographic and genetic input of immigrants, and a lower chance of recolonization after local extinctions (Lande 1988).

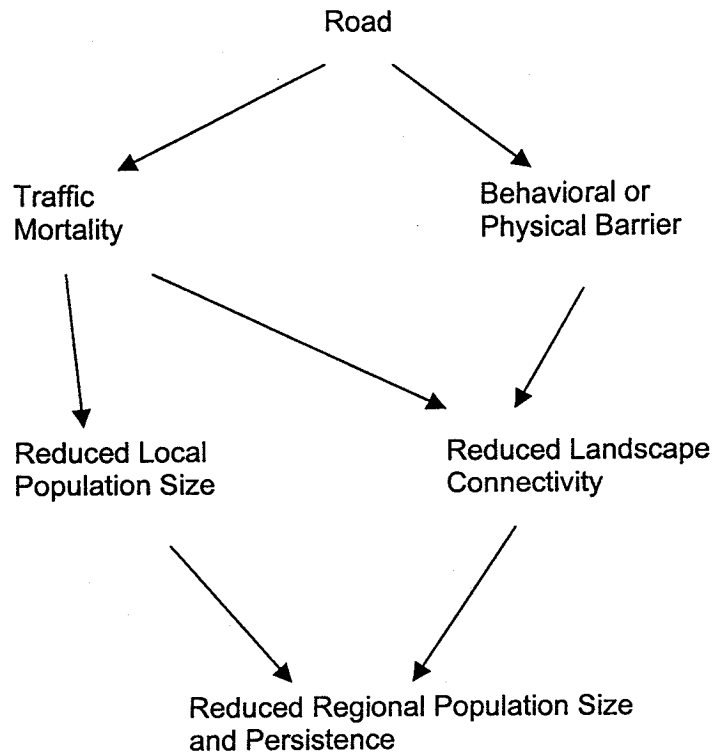


FIGURE 13.1. Roads affect regional persistence of wildlife populations through (1) directly increasing mortality and (2) directly and indirectly (through mortality) decreasing landscape connectivity.

A *corridor* is a linear landscape feature that facilitates movement between resource patches, and it may increase the interchange of individuals between local populations. This may increase the persistence of local and regional populations (see metapopulation dynamics and rescue effect below). On the negative side, corridors can facilitate the spread of exotics, disease, and disturbances (Wiens 1996). There is little evidence that animals are more likely to move along roads or roadsides than through other habitats. Unpaved, narrow roads may be used by large mammals such as lions (*Panthera leo*), cheetahs (*Acinonyx jubatus*), dingos (*Canis dingo*), coyotes (*Canis latrans*), foxes (*Vulpes sp.*), wolves (*Canis lupus*), and tasmanian devils (*Sarcophilus harrisi*) (Forman 1995). Pocket gophers (Geomyidae), meadow voles (*Microtus pennsylvanicus*), and heathland ground beetles appear to have expanded their ranges by using roadside verges as dispersal routes (Vermeulen 1994; Forman 1995). Probably the best evidence of roadsides as corridors is the dispersal of disturbance-adapted plant species. Sludge from a carwash in Canberra, Australia, contained viable seeds from 259 plant species, indicating movements of up to 100 km along roads based on the nearest possible seed sources (Wace 1977).

A *metapopulation* is composed of a group of local populations linked by movement. By definition, local population dynamics are asynchronous, such that not all local populations undergo extinction at the same time—a process known as *spreading of risk* (Den Boer 1968). Movement rate between local populations permits recolonization of local extinctions, but this rate is not so high that the local population dynamics become synchronized (Hanski 1989). Interpatch movement is the defining characteristic of metapopulations, and therefore metapopulations depend on landscape connectivity for persistence. Roads can disrupt connectivity, thereby reducing metapopulation persistence. Movement between populations also reduces local extinction probability by rescuing populations from low numbers (the *rescue effect*; Brown and Kodric-Brown 1977). By reducing connectivity, roads reduce the potential of the rescue effect to support regional populations.

In addition to affecting between-population movements, landscape structure also affects the ability of an individual animal to move among different landscape elements to meet its life-history demands. The scale at which such movements occur is defined by the organism's *ecological neighborhood*, the region within which it is active or has influence (Addicott et al 1987). High connectivity of habitat patches containing nonsubstitutable resources (*landscape complementation*) and substitutable resources (*landscape supplementation*) enables an organism to collect resources efficiently, resulting in lower mortality, higher reproduction, and ultimately larger populations (Dunning et al. 1992; Pope et al. 2000). When roads act as barriers to movement, they reduce landscape complementation and supplementation by reducing accessibility of resources.

13.3 Recent Applications

We surveyed the primary literature and the secondary literature (mainly conference proceedings), and we informally surveyed individuals at the 1999 International Association for Landscape Ecology World Congress meeting in Colorado, looking for examples of applications of landscape ecology that address road impacts. For the most part, the concepts outlined in Section 13.2 have not been explicitly applied to road effects on biological conservation. Nevertheless, various measures to compensate for the negative impacts of roads ("mitigation measures") have been applied and can be considered in a landscape ecological context. Such measures are intended to mitigate the effects of roads on either (1) landscape composition, by reducing road effects on habitat loss and quality, or (2) landscape connectivity, by increasing successful movement of organisms across roads. Due to the recent nature of most mitigation projects, existing performance evaluations measure only whether individual organisms reacted positively. The success of these measures at the population level has yet to be assessed.

The mitigation measures we highlight were developed based on the assumption that roads are needed. However, the most effective methods to reduce road impacts are to remove roads, or to reduce the physical size and traffic volume of

roads (e.g., through better public transportation, increased gas taxes, and reduced commuting distances).

When roads must be built, the proper placement of a road is the best mitigation measure. This requires knowledge of the landscape and the distributions and movement patterns of the wild populations of concern. A good example is the decision to extend the Florida Turnpike (USA) so that it bypasses rather than bisects two state forests. Placing the road through high-quality wildlife habitat would have resulted in habitat loss and fragmentation, edge effects, and mortality of the low-flying, threatened Red-cockaded Woodpecker (*Picoides borealis*) (Gilbert 1998). Plans also are being formulated to prevent secondary impacts from development pressures caused by the Turnpike (Gilbert 1998).

Measures for mitigation against habitat loss involve limiting rights-of-way and clearing activities to as small an area as possible (Gilbert 1998). For example, eliminating debris, erosion, and sedimentation in waterways crossed by roads has been successful in maintaining intact mussel habitat in North Carolina, USA (Savidge 1998). Creating alternative, accessible habitat has shown some success with amphibian spawning grounds in western Europe (Langton 1989). The Florida Department of Transportation has created and manages six regional mitigation parks to "offset" development impacts to threatened species (Gilbert 1998). To truly mitigate habitat loss, the new habitat must be placed within the ecological neighborhood of existing populations of the species of interest. Designating already existing habitat as "protected" or creating isolated habitats does not replace lost habitat.

Various measures have been implemented to mitigate effects of roads on the quality of roadside habitat. Educating roadside workers on low-disturbance work practices and the value of roadside habitat has had success in Australia (Straker 1998). Roadside vegetation screens and earthen berms can be used to reduce visual and noise disturbance in habitat adjacent to roadways (Tewes and Blanton 1998). Disturbance of ungulates by highways was lower when shielding was present (Ward 1973, cited in Singer and Doherty 1985). Eliminating or reducing light pollution by directing all lighting toward the road surface may be necessary before cougars (*Felis concolor*) will use roadside habitat (Beier 1995). Reduced habitat quality due to disruption of water flow by roads can be mitigated using properly placed culverts. The open-bottomed culvert and bridge of relatively large size allow fish passage and normal flow of water, and they reduce debris accumulation (Thomas 1998).

The main effect of roads on habitat quality is through increases in wildlife mortality. Faunal traffic mortality can be reduced by modifying either wildlife behavior or human behavior. Some animals are attracted to roads because roads offer food in the form of roadkill, basking animals, spilled grain, and road salt (Forman and Alexander 1998). Removing these sources of food reduces the likelihood that attracted individuals will be on the road and vulnerable to traffic (Straker 1998). An effective deterrent to wildlife traffic mortality is to erect a physical barrier such as a fence (Jackson and Griffin 1998). The fence must be sufficiently tall, long, solid, and deep in the ground to stop animals from going over, around,

through, or under it. An improperly installed fence that permits animals to enter the road may trap the animals on the road, thus increasing mortality (J. Duquesnel, personal communication).

Creating a complete barrier limits the risk of traffic mortality but also reduces landscape connectivity, which could have negative consequences for the regional population. Measures permitting animals to cross roads safely simultaneously mitigate direct effects of mortality on local populations and indirect effects on landscape connectivity (see Figure 13.1). One such measure is the placement of light reflectors, which are designed so that light from car headlights hits a reflector and is reflected perpendicular to the road and, in theory, into the eyes of approaching wildlife. The light is assumed to frighten animals and cause them to retreat from the road edge when a car is on the road. Reflectors have shown mixed success for deer in North America and small mammals in Australia (Armstrong 1992; Straker 1998). Animals appear to become habituated to the light and eventually disregard it (A. P. Clevenger, personal communication). In addition, where there is an embankment along the road, the light may shine over or under the head of the approaching animal. Reduction in traffic mortality after installation of reflectors in Australia was probably due to increased driver awareness rather than deterrence of animals (Straker 1998).

Human behavior can be modified by raising awareness of wildlife traffic mortality and limiting human use of roads. The most common measure is the installation of wildlife crossing signs to raise driver awareness. However, this is of limited value, especially when the animals are rarely seen (Pafko and Kovak 1996). Reducing speed limits is more effective. Yellowstone National Park (USA) instituted a speed limit of 73 km/h (45 mph) when they determined that vehicle speed was the primary factor contributing to vehicle-wildlife collisions. They found that road design, such as uneven surfaces, more curves than standard highway specifications, and narrow pavement width, was more effective at reducing vehicular speed than were posted signs (Gunther et al. 1998). An effective measure that works on a site-by-site basis is road closures during times of high wildlife activity. On Phillip Island, Australia, nighttime curfews and restricted access to a subdivision during peak penguin activity resulted in a 10-fold reduction in Fairy Penguin (*Eudyptula minor*) roadkill (Straker 1998).

Other methods for increasing permeability of roads to wildlife involve installation of wildlife crossing structures, i.e., underpasses or overpasses. Underpasses are spaces created under the road and include tunnels, culverts, and areas under bridges. Modifications to existing culverts and bridges so they can be used by animals include adding a raised platform in culverts to provide dry passage, and extending bridges on land so that animals can travel along the bank of the waterway. Overpasses are small-scale land bridges that extend over the road. Overpasses can be vegetated to allow for seminatural crossing conditions.

Research on wildlife use of crossing structures has focused largely on ungulates (deer, *Odocoileus virginianus*; elk, *Cervus canadensis*; mountain goats, *Oreamnos americanus*), panthers, and amphibians (e.g., Singer and Doherty 1985; Langton 1989; Foster and Humphrey 1995; Clevenger 1998). Ungulates

and panthers have successfully used underpasses, but results are mixed for amphibian tunnels. In the Foster and Humphrey (1995) and Clevenger (1998) studies, several other mid-sized and large animals such as bobcats (*Felis rufus*), coyotes, and raccoons (*Procyon lotor*) were found to use underpasses frequently. Occasional users included alligators (*Alligator mississippiensis*), black bears, wolves, and cougars. Smaller underpasses (<1.2 m high) are used by small mammals such as mice and rabbits, amphibians and reptiles, and mid-sized carnivores such as badgers, foxes, and wildcats (*Felis sylvestrus*) (Yanes et al. 1995; Bekker and Canters 1997). Rodriguez et al. (1996) found that the most important factor determining vertebrate use of culverts under a high-speed railway was the proximity of the passage to the species' habitat.

Clevenger and Waltho (1999) investigated the effects of culvert design and placement on crossing frequencies of eight small- and medium-sized mammals. They found that species differed in their responses. For example, coyotes and martens (*Martes americana*) had a tendency to use older culverts, whereas weasels (*Mustela* sp.), snowshoe hares (*Lepus americanus*), and red squirrels (*Tamiasciurus hudsonicus*) used newer culverts. Culvert use by red squirrels and voles (Arvicolinae) was negatively correlated with culvert openness, whereas use was positively correlated with openness for coyotes. Amount of forest cover nearby, distance to cover, or both affected culvert use by some species. The higher the traffic volume, the greater the use of culverts by martens, weasels, hares, red squirrels, and voles, whereas coyotes used culverts less in high traffic density situations.

Vegetated overpasses may be more successful than underpasses because they are quieter; are less constricting; maintain more natural conditions through the presence of soil, vegetation, and small ponds; and have ambient conditions of rainfall, temperature, and light (Jackson and Griffin 1998). Overpasses appear to accommodate a greater range of organisms, because they can serve as both passageways and as habitat for small mammals, reptiles, amphibians, and invertebrates. Width of overpasses is a crucial element for effectiveness; narrow (<50 m) overpasses are associated with fewer wildlife movements (Keller and Pfister 1997).

Crossing structures do not need to be spaced as closely together for large mobile species as they do for smaller animals. Also, Rodriguez et al. (1996) and Clevenger and Waltho (1999, 2000) found that some species preferentially use large culverts, whereas others prefer small ones. Therefore, a variety of sizes of structures is likely to represent a cost-effective strategy that will provide for both large and small species. Roadside fencing that funnels animals to the structures and prevents them from crossing the road at other places is considered important for the success of most crossing structures (Jackson and Griffin 1998). Despite the clear benefits of crossing structures for facilitating faunal movement, there have been no empirical tests of their effect on population abundance or persistence. To date, there are no mitigation measures to address the negative impacts of "road corridors," such as the spread of exotics.

13.4 Principles for Applying Landscape Ecology

As discussed above, the potential landscape-scale effects of roads on natural populations are significant and widespread. Roads affect many species at once, but to varying degrees and in different ways depending on how the species' movement and demographic characteristics interact with landscape structure, which includes the road network. Principles for successful mitigation require that the task be simplified without compromising the effectiveness of the mitigation. Based on these criteria, we suggest three principles for successful mitigation.

First, the species most vulnerable to road effects should be identified. Several life-history and population traits contribute to the vulnerability of faunal populations to road effects. Large carnivores are inherently vulnerable because they exist in low densities, have low population growth rates and large home ranges, and require large amounts of interconnected habitat (Ruediger 1998). Forman and Alexander (1998) suggest that sustainable populations of large carnivores are possible only in landscapes containing road densities below about 0.6 km/km². The average road density in the United States is 1.2 km/km² (Forman and Deblinger 1998), and average road density in many European countries is over 2 km/km² (European Commission 1999). Generally, species that occur in low densities and have low reproductive rates and long generation times (many threatened and endangered species) are poor at recovering from additional mortality. Highly vagile species, with large home ranges or life cycles that require shifts in habitat, are more likely to encounter roads and be subjected to their effects. Species that depend on more than one habitat (landscape complementation) are particularly susceptible to habitat loss and reduced landscape connectivity. For example, Carr and Fahrig (2001) found that leopard frog (*Rana pipiens*) populations were more vulnerable to traffic mortality than were green frog (*Rana clamitans*) populations, possibly because of the leopard frog's higher vagility and greater reliance on landscape complementation.

A species' vulnerability also depends on the state of its habitat. Species in landscapes with low amounts of habitat are likely already close to an extinction threshold and, therefore, are vulnerable to additional habitat loss and mortality from roads (Fahrig 2001). Fragmentation effects of roads also will be more severe in landscapes containing low amounts of habitat (Fahrig 1998).

The second principle is that mitigation measures should target the most vulnerable species. For example, removing food trees along roadsides except at an underpass as a funneling measure may work for the koala (*Phascolarctos cinerus*) (Straker 1998) but is detrimental to other species that depend on those trees. Installing culverts may allow the flow of aquatic species but not terrestrial species. Species that exhibit behavioral avoidance due to noise will not use overpasses unless traffic noise is reduced in the area. If most traffic mortality occurs during seasonal migrations, then closing roads during these migration periods can reduce mortality.

The third principle is that mitigation measures should be evaluated based on their effectiveness to reduce population-level impacts for a variety of species

and landscapes simultaneously. Here we attempt a ranking of measures in this context, based on current knowledge. First, the most general and influential measure is to reduce the number of roads (existing and new) and vehicles. This would result in the greatest reduction of road impacts for every species. No amount or combination of other mitigation measures can attain the effectiveness of eliminating roads. If a road must be built, the most effective measure is to build the road completely below ground as a tunnel or (less effective) above ground as a viaduct. However, due to the cost of such construction, these measures are likely only feasible over short distances to avoid critical habitats (see below). A more practical solution is to place the road where it is least likely to have an effect on wildlife. When the objective of a new road is primarily to accommodate increased traffic volume to existing destinations, new roads should be placed in already developed areas near other roads, or existing roads should be expanded to increase traffic volume. This would result in a smaller additional effect than would building a new road through undeveloped natural areas. Expansion of an existing road also may result in a road-effect zone that is smaller than is the total road-effect zone of two separate roads (but see Section 13.5).

These measures may not be acceptable options when the objective of a new road is to create a more direct link between locations. In this case, construction of the new road will likely result in unavoidable loss and fragmentation of habitat. Where this occurs, mitigation measures should increase the ability of animals to move successfully across (under or over) the roadway. The most successful of such measures are those that maintain critical stretches of habitat intact. This is most effectively done by building sections of the road to avoid the habitat (i.e., build a road bridge or tunnel), as opposed to placing the road through the habitat and then reconstructing the broken link (i.e., wildlife overpass or tunnel). If the road is already in place, wildlife overpasses, wildlife tunnels, and fences should be used.

13.5 Knowledge Gaps

Little or no research has been conducted explicitly to study the effects of roads on landscape processes, and mitigation measures have been applied largely without consideration of landscape-scale effects. Therefore, the scope for research in this area is almost limitless. However, some knowledge gaps are particularly problematic. The most critical gap is in the area of design principles for landscape planners. To date, landscape-scale ecological considerations in design of road networks have been nonexistent at worst and post hoc, ad hoc, or both, at best. Well-designed studies are needed to form the basis for such design principles. Theoretical work is needed to derive design principles, whereas empirical work is needed to provide realistic input assumptions for modeling studies as well as to test resulting theoretical predictions.

13.5.1 Theoretical Voids

Currently, the only theories linking roads and landscape ecology concepts are the verbal arguments in Section 13.2. Quantitative theory is needed to address the following three questions.

First, under what conditions is the impact of one large road less than that of several smaller roads? The answer to this depends on the road-effect zone, which varies among species with different behaviors and vulnerabilities to road impacts. Expanding an existing road rather than building a new road may be more costly, given higher land prices in already developed areas, and it may result in less-efficient human travel. Justification of this action therefore requires evidence that there is an overall benefit to regional wildlife populations.

Second, are there general indices of landscape structure that can predict impacts of different road pattern scenarios for different species guilds? Here, a guild is defined as a set of species with similar life-history and movement attributes. The effect of roads on population survival depends on species' traits, the road pattern, and the landscape structure. Predicting such effects for many species in a particular landscape is therefore likely to require a complex multispecies analysis. It would be of great value to know whether there are robust measures of landscape structure (including the road pattern) that can be used to draw reasonable conclusions without requiring highly complex multispecies analyses.

Third, can one derive an optimal mitigation strategy, such that landscape connectivity can be restored for the largest number of species at the lowest possible cost? The goal would be an algorithm for predicting the optimal distribution of types, sizes, and spacing of mitigation measures for a given set of species and a given road pattern. The objective is to move away from ad hoc solutions for individual species, but also (as above) to avoid the need for building a complex multispecies landscape-scale simulation model for each road development.

13.5.2 Empirical Voids

Many of the relationships between road effects and landscape ecology concepts (Section 13.2), as well as much of the collective wisdom regarding mitigation measures, are based on assumptions and inferences rather than on empirical evidence. Empirical research is critically needed in at least five areas.

First, studies documenting the population-level effects of roads are needed. Counts of traffic mortality victims can reach the thousands (Ashley and Robinson 1996). However, only a few studies have demonstrated significant population-level impacts of roads (e.g., Reh and Seitz 1990; Fahrig et al. 1995; Reijnen 1995). Transportation agencies may require this kind of evidence to justify expensive mitigation efforts (D. McAvoy, personal communication).

Second, empirical studies are needed to determine the size of the road-effect zone. Forman and Deblinger (1998) provide a rough estimation that 15% to 20% of the land in the United States is directly affected ecologically by roads. Indirect

effects of roads on individual species or guilds can extend out to at least 1 km (Findlay and Houlihan 1996; Carr and Fahrig 2001). Such information is needed for a wide range of taxa to build an understanding of the cumulative scale of roads on the landscape.

Third, the responses of wildlife individuals and populations to traffic may include threshold phenomena. For example, there may be a threshold in traffic volume above which the probability of safe crossing drops to near zero. Similarly, there are likely threshold effects of traffic mortality on the regional population, in which a small increase in traffic volume has a large effect on persistence of the regional population (Fahrig 2001). If such thresholds occur but their locations (in terms of traffic volume) are unknown, then gradually increasing traffic volume could lead to precipitous crashes of wildlife populations when the threshold is (unknowingly) crossed. Knowledge of such thresholds is therefore critical.

Fourth, studies are needed to quantify the separate effects of traffic mortality on local population persistence and landscape connectivity. Traffic mortality eliminates individuals that would have contributed to both local population dynamics and regional population survival through movement. If loss of individuals from the local population causes the greatest impact, then blocking the population from crossing roads is a feasible mitigation option. For example, Henein and Merriam (1990) showed that decreasing structural connectivity of a landscape can increase population persistence if dispersal mortality is high. If traffic mortality is a significant factor at both the local and regional levels, then reducing mortality and enhancing landscape connectivity are both needed for mitigation.

Fifth, few studies quantitatively test and compare effectiveness of different mitigation structures and identify the factors important for their effectiveness. Cleverger and Waltho (1999, 2000) conducted such analyses for wildlife underpasses. However, many widely held assumptions, such as that wildlife overpasses are generally more effective than are wildlife underpasses, remain untested.

13.6 Research Approaches

13.6.1 Approaches for Theoretical Research

The theoretical research questions identified in Section 13.5.1 could be addressed by conducting simulation experiments using a generalized landscape-scale spatial model of animal population dynamics and movement. Such a model would not be tailored to a particular species or landscape, but would be general and flexible enough to represent different species guilds and landscape structures by altering parameter values. The approach would be to develop general principles by conducting many simulation runs in an experimental design, in which parameter values are changed systematically between runs. Principles would then be derived from the relationships between the parameter values and population response variables such as population abundance and persistence (Fahrig 1991).

This approach could be used for all three theoretical research questions. To compare effects of one large versus several small roads, simulations would be conducted for a range of landscape structures and species guilds to determine how these factors affect the tradeoff between size and number of roads. Indices of landscape structure for predicting road impacts could be developed by conducting simulations in which landscape structure (including road pattern) is systematically altered between simulation runs, and the effects on regional abundance and persistence of species guilds are determined. The results would then be analyzed to determine whether there are indices of landscape structure that can predict the simulated road impacts (e.g., Schumaker 1996). The question of optimal mitigation strategies would require the added step of incorporating economic costs of each mitigation measure. Different simulation runs would be conducted with different mitigation strategies. Model output would be the population response and the cost of the mitigation strategy. The optimal mitigation strategy for a given road pattern would be the one that produced acceptable abundance and persistence levels for wildlife populations (using predefined criteria) at the lowest cost.

13.6.2 Approaches for Empirical Research

Success of these theoretical studies would depend on availability of realistic parameter values, generated from empirical studies. Critical empirical information for model input includes (1) road-effect zones for different species, (2) threshold values of species' responses to roads, and (3) information on responses of various species to different mitigation structures.

Two general sampling designs are appropriate for empirical studies of road effects on wildlife populations. The first is road-centered, in that the road is the focal point of study and the wildlife population is sampled in the surrounding landscape (e.g., Reijnen 1995; Fahrig et al. 1995). The second design is habitat-centered, in that a habitat type of interest is the focal point of the study. The wildlife population is assessed within the habitat patch, and the predictor variable is the length of road or amount of traffic in the landscape surrounding the patch (e.g., Findlay and Houlihan 1996; Carr and Fahrig 2001).

The road-effect zone could be determined using either approach. Using the road-centered approach, several transects could be run perpendicular to the road(s). Along each transect, response variables, such as abundance of individual species or species richness, would be measured. By plotting the mean response against distance from the road, one should detect a maximum distance at which there is no change in the response. This distance defines the road-effect zone.

The habitat-centered approach also could be used to estimate the road-effect zone. Road (or preferably traffic) density would be calculated in concentric circular landscapes of increasing diameter around patches of the habitat type of interest (e.g., wetlands: Findlay and Houlihan 1996; ponds: Carr and Fahrig 2001). The response variable (e.g., population density, species richness) would be measured in each focal habitat area, and the predictor variable would be road density

in the circular landscapes around each focal habitat. If traffic volume information is available for all roads in the landscapes, traffic density rather than road density would be used because traffic density integrates the length of road in the landscape with the traffic volume on those roads (e.g., Carr and Fahrig 2001). A separate analysis would be conducted for each landscape diameter. The strength of the relationship (e.g., R^2 value) between road density and the response variable(s) should increase with increasing diameter of the landscape, up to a critical diameter, which determines the road-effect zone.

Either the road-centered or the habitat-centered approach could be used to identify thresholds in the relationship between traffic volume and population densities in adjacent habitat. For the road-centered approach, the sample would need to include roads with a wide range of traffic volumes. For the habitat-centered approach, one would need habitats situated in various landscapes whose traffic densities varied widely. The relationship between population density and either traffic volume (road-centered approach) or traffic density (habitat-centered approach) would then be examined for evidence of a sharp drop or threshold in population density at a given traffic volume or traffic density.

Local population and regional population (Figure 13.1) effects of road mortality could be separated using a road-centered, multilandscape experiment. In each landscape, three treatments would be applied, each to a different local population. In the first treatment, a barrier (e.g., a fence) would be installed on the other side of the road from the population. In the second treatment, a barrier would be installed on the same side of the road as the population. And for the third treatment, no barrier would be installed. Therefore, the first population would experience both loss of individuals (local impact) and the barrier effect (regional impact), the second would experience only the barrier effect, and the third would experience only loss of individuals. Abundances of all populations would be monitored. If the results showed no difference in mean abundance between populations experiencing both mortality and the barrier effect and populations only experiencing the barrier effect, then one would conclude that local mortality is of little import and impact of roads on landscape connectivity is the main concern. If there is no difference in mean abundance between populations experiencing both mortality and the barrier effect and populations only experiencing mortality, then one would conclude that local mortality has a relatively greater impact than does the barrier effect and connectivity is not the main concern. Note that this experimental design would work regardless of the direction of animal movement.

Empirical studies to compare different mitigation measures could be conducted using the road-centered approach. The study design would depend on the degree of control the researcher has over installation of the mitigation structures. In the ideal situation, a multilandscape design would be used in which, in each landscape, each type of mitigation structure would be built on different segments of the same road. Wildlife populations near the road would be monitored before and after construction both near the structures and in control locations where no mitigation structure was built. Statistical analyses (e.g., analysis of variance) would be used to test for differences among mean population responses due to the dif-

ferent structures. In reality, however, this level of control is unlikely to be available to the researcher. To compare different types of mitigation measures using existing structures, populations near the structures (and control populations near the roads in locations where no structure exists) could be sampled for a very large number of structures. The large sample size would be necessary so that uncontrolled variables, such as length of time since a structure has been in place, could be included in the statistical analyses.

13.7 Conclusions

Addressing the impact of roads on the landscape is a daunting task. Roads affect landscape structure and species survival in many ways, through traffic mortality, habitat fragmentation, habitat loss, and changes in the quality of the surrounding habitat. Although the most visible impact, traffic mortality, brought the issue of roads to public attention, closer examination of the issue has brought some important questions to light. What is the overall impact of roads, especially when the landscape is already under stress? To what extent are roads responsible for species' declines? Answering these questions is an important task, as preliminary studies indicate that roads could be a far greater force in population declines than previously thought.

Although mitigation measures are being developed and perfected to deal with some of the impacts of roads, they rely on the assumption that roads are a necessary evil. However, most mitigation measures have a limited potential in their ability to reduce impacts for a large number of species over large areas. The best method from a biological conservation viewpoint is to alter human values and behavior such that our dependency on roads is reduced.

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