REPAIRING ROAD SYSTEM IMPACTS ON LANDSCAPE CONNECTIVITY

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Abstract: Landscape fragmentation disrupts ecological flows, reduces wildlife movement, and imperils aquatic and terrestrial systems. Two primary drivers of fragmentation are human land uses and transportation systems, which also influence each other. One aspect of road ecology is the study of the effects of road systems and road use on ecological flows (e.g., wildlife movement). At national and state scales, agencies and scientists are investigating the ways that roads and traffic fragment landscapes and ecological processes. Most contemporary research points to the importance of existing road and highway systems in reducing habitat quality and imperiling species. One way that state and federal transportation agencies are responding to this is to improve wildlife-highway interactions through constructed crossings and modified traffic patterns. These activities are consistent with federal transportation law (SAFETEA-LU) and the California Wildlife Conservation Strategy, which lists habitat fragmentation as a major stressor on wildlife. Another current activity is the proposed "Statewide Connectivity Project," a collaboration among state agencies, universities, and non-governmental organizations. Critical in active crossing facilitation is evaluation of the effectiveness of the management action, in order to inform future decisions. A combination of focused research, wildlife crossing facilitation, and supportive policy will create an environment where we may repair some of the lost connections across the landscape.

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Road systems have many effects on natural and human systems. The study of these effects defines "road ecology". The effects include: habitat loss and fragmentation, runoff impacts on water quality, facilitation of non-native species invasion, air quality impacts, and transformation of local and regional land-use. Some of these effects can be remediated, linking road ecology to restoration ecology. Specifically, the effects of individual roads and highways and the effects of road systems can be alleviated through smart planning (avoiding harm) or infrastructural solutions (restoration from harm).

The geographic sum of effects of roads on human and natural systems can be thought of as the "road-effect zone" (Forman et al. 2002). This is a useful conceptual framework for theoretical development of road ecology and as a way to frame research, planning, and mitigation of road-system impacts. The effects of individual roads will depend on the interaction between the roadway and its traffic with the wildlife, plant communities, hydrology, and other natural systems and flows present in the vicinity. The effects of larger systems or networks of roads are more complex, consisting of the effects of each road segment, as well as emergent properties of road systems, such as habitat fragmentation and local wildlife extirpation.

In this paper, I review the impacts of roads and road system development on landscape connectivity. Roads and associated land development can fragment landscapes and reduce ecological flows across landscapes and among habitat patches. I primarily describe impacts to wildlife movement, with some reference to other flows, and finish with potential mitigation solutions.

FRAGMENTATION

Landscapes naturally exist in fragments (Fig. 1A), which is recognized in the ecology literature as "patchiness" and which has effects on fauna (Watling and Donnelly, 2006) and plant species richness (Chust et al., 2006). Exchange of energy and material (including organisms) occurs among these fragments (arrows in figure), with the type, timing, and quantity depending on the fragments' proximity, habitat types, and type of ecological flow. The insertion of roads into landscapes can interrupt many flows and exchanges among fragments (Fig. 1B) and lead to an effect generally known as "fragmentation." The type and quantity of fragmentation depends on the nature and uses of the roads.

Functional Fragmentation

Physical fragmentation of landscapes by road systems can cause functional fragmentation. Although physical and functional fragmentation are related to each other, they are also worth considering independently. Functional fragmentation, or its corollary functional connectivity, emerges from physical fragmentation and can only be remediated by considering the presence *and* use of infrastructural elements and their impacts on functional connections across a landscape.

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Scale

Fragmentation can have impacts at many scales. At the most local scale at which studies tend to occur (meters to kilometers), impacts include barrier effects (citation), aversion effects (Gill et al. 1996, Mac et al. 1996, Reijnen et al. 1997), and mortality sinks (Madsen 1996, Rubin et al. 1998). At the scale of single dominant habitat types (e.g., grassland) or taxa (e.g., foxes), measurable effects on population dynamics and intra-habitat natural processes may occur (Pichancourt et al. 2006, Smith and Batzli 2006, Stephens et al. 2005). At the landscape scale, several to many habitat types and many taxa may be affected, large-scale natural processes (e.g., fire) may be modified, and whole ecosystems may be affected (Bolliger et al. 2005).

Range of Fragmentation

Fragmentation by human actions is an evolving process. Low-intensity land-uses and low-density road systems may cause the least fragmentation, industrial and urban areas may provide the most. Fragmentation occurs as a continuous variable across our landscapes and is often analyzed on continuous scales (e.g., road density calculation in a grid; Trombulak and Frissell 2000). Simply measuring physical fragmentation is part of the story and is relevant to certain processes (e.g., hydrologic effects; citation). However, use of the fragmenting infrastructure for human activities (e.g., transportation) is just as critical in understanding functional fragmentation (e.g., wildlife movement; Putman 1997, Riley 2006). At the natural end of the scale (e.g., roadless forested landscapes), natural fragmentation may dominate landscape patterns. Once landscapes are used for logging, rural sub-division, and grazing, there is intermediate to severe physical and functional fragmentation and artificial fragmentation may dominate natural fragmentation. At the extreme end of the fragmentation range (e.g., urban areas) there may be very little left of natural habitats to connect, but other natural processes (e.g., water cycle) may be severely affected.

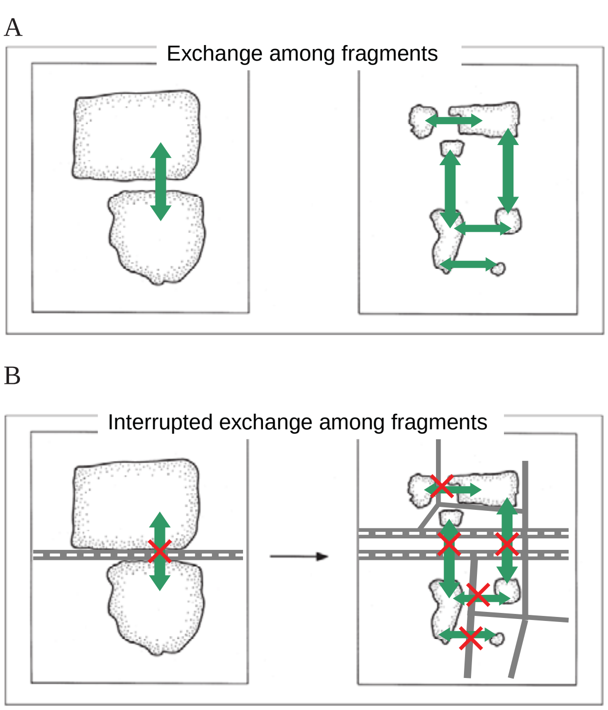

Figure 1. Fragmentation of landscapes and habitats and interruption of flows by road development.

ROAD, RAIL AND HIGHWAY SYSTEM IMPACTS

Road-kill

Traffic-caused wildlife mortality (road-kill) is a result of highway development. All terrestrial vertebrate and invertebrate taxa (including birds and flying insects) may be killed by vehicles moving along transportation corridors. Individual roads, railways, and highways may exact significant tolls on wildlife populations. This can result in local extirpation, abandonment of important habitats and migration corridors, and local population sinks. Certain taxa must move regularly between two adjacent areas separated by roadways (see text box). There are several critical things to remember about road-kill: 1) absence of road-kill does not indicate the absence of an impact to a species; 2) road-kill represents a continuing and usually un-mitigated impact of a facility; 3) numbers and species of road-killed animals must be compared to population structure and size to understand impact of the mortality on the species.

Population Viability

There have been few studies of the impacts to populations of road-kill. The remaining Florida panther (*Felis concolor coryi*) population is thought to be heavily-impacted by regional highway traffic (Land and Lotz 1996). As society develops more and more roads and highways in areas with few or no roads, it is likely that populations of many species and very localized species will be threatened. There have been few studies of the actual impacts of existing and new roads/highways on population viability, but it is an essential step in understanding and remediating damage from our development.

Extinction

The absence of road-kill does not mean that there has been no impact to a specific wildlife species or population. There may have already been one or more populations that no longer occupy suitable habitat because of roads/highways/railways and traffic along them. This local extinction may be because wildlife no longer occupy an area that has experienced increased development, or because there have been sufficient road-kill and barrier effects from the transportation corridors to eliminate a population. When these same ideas are carried to the species level, a whole species may be imperiled or actually go extinct.

ANALYZING CONNECTIVITY

A critical component of preventing and repairing the damage caused by road, highways, and land development is analysis of the impacts and threats to connectivity (the corollary to fragmentation). Connectivity is a physical-structural as well as functional concept, so analyzing connectivity requires analysis of both physical patterns on the landscape and changes in the processes on the landscape.

Bio-physical Connectivity

Patterns and structure in landscapes and habitat types provide the architecture that determines flows and connections across the landscape. Wildlife species may require connections among patches of identical habitat types, or among different habitat types needed at different times of day, seasons, or life cycle phase. Most landscapes are a combination of natural features (e.g., plant communities) that function as the biological context and artificial features (e.g., canals, roads, power transmission lines) that cause physical discontinuities in the landscape. Landscape patterns, structure, and connections are often used as surrogates for wildlife species and population well-being. In highly constrained settings (e.g., wildlands adjacent to urban areas), easily-identified corridors may function as the only connection available (Penrod et al. 2006). However, in most landscapes and habitat types, connectivity emerges from a combination of corridors, stepping stones (stop-over habitat), and "matrix" (less-desirable habitat) in complex interaction (e.g., Baum et al. 2004). Emergent biological properties of landscape connectivity are assumed to provide benefits to wildlife and other species. Physical disruption of landscape patterns and structure can therefore affect these emergent biological properties. In the absence of comprehensive information about wildlife occurrence, movement, and population dynamics, landscape connectivity is best measured as a function of connecting and disrupting elements.

Focal/Umbrella Species

Studying impacts of fragmentation on all species is a daunting prospect. A popular remedy is to study connectivity in terms of impacts to a select group of species. *Focal species* are the subject of intensive study of impacts and individually may be intended to represent a larger group of species. *Umbrella species* are intended to represent large groups of related or un-related taxa, usually in the context of landscape analysis. There are problems and benefits to the uses of focal and umbrella species to study connectivity (see Lindenmayer et al. 2002 for a thorough critique). Some problems are obvious, like failure of a suite of species to represent all species, including ones that are rare or that have legal protection. Less obvious problems include incomplete knowledge about species' habitat use, cycles in population structure, movement, interactions among species, and changes in habitat utilization in response to land-use or climate change. Often information is not available about actual species distribution on disturbed landscapes and analysts instead use models of wildlife distribution that are based on bio-physical habitat patterns/structure. A cautious use of a suite of species to generally represent a larger, albeit unknown, group of wildlife species may provide important information about potential effects of fragmentation and benefits of connectivity. However, it is probably a mistake to only use wildlife species' occurrences or modeled distributions in the absence of information about landscape patterns and structure.

Integrated Analysis

Most contemporary analyses of connectivity/fragmentation use an integrated combination of bio-physical habitat characteristics and modeled focal species habitat (e.g., Shilling and Girvetz 2007). Others take into account possible effects of projected land development and/or climate change on plant communities and thus wildlife habitat (Lindenmayer and Fischer 2006). A truly integrated analysis of landscape connectivity would take into account all of these factors and others. Others include: possible market effects on agricultural and urbanizing landscapes, roles of land management in actual habitat quality, and changes in natural ecological processes at various scales. An integrated analysis including these ecological and social factors should be the basis for contemporary investments in restoring lost connectivity.

REPAIRING AND MITIGATING LOST CONNECTIVITY

Connectivity lost to human activities is often repairable. Restoration of lost connectivity due to development and extraction is usually the most expensive conservation option. Far cheaper is the avoidance of the loss in the first place. This is one reason why "avoidance" is the first mitigation activity recommended by agencies such as the U.S. Fish and Wildlife Service when dealing with endangered species, protected habitats, waterways, and other ecosystem features. The Federal Highway Administration sponsors approaches to conservation that take into account the place that highway facilities have in the ecological and human context (so-called "context-sensitive planning"). Besides the many scientific studies describing lost connectivity, "Wildlife Action Plans" developed within each state recognize habitat fragmentation as one of the primary threats and harms to wildlife species and populations. The next few sections describe different planning processes in California that deal with or could deal with protection and repair of lost connectivity. Each planning process is an opportunity for wildlife biologists and conservationists to advocate for restoring and protecting connectivity to benefit wildlife.

Planning Approaches

"California Wildlife: Conservation Challenges" (otherwise known as the California Wildlife Conservation Strategy [CWCS]) was developed by the California Department of Fish and Game to provide the foundation for future state-sponsored protection of wildlife. The CWCS described habitat loss and fragmentation as two of the greatest threats and existing harms to wildlife habitat and species. The Plan prioritized identification of wildlife connectivity areas and the early integration of this information into state, regional, and local planning processes. The loss and fragmentation occurred and is still occurring because of land-uses (e.g., rural subdivision) allowed by local municipalities and transportation system development by state and local agencies. Because these institutions act under legislated license and are theoretically acting in the best interest of Californians, planning and policy options exist to change practices that might otherwise result in more fragmentation. How the CWCS will be implemented, either directly or indirectly through state policy remains to be seen.

The federal legislation known as "SAFETEA-LU" (Safe, Accountable, Flexible, Efficient Transportation Equity Act, A Legacy for Users) governs those activities of local and state transportation agencies that use federal funding to develop transportation facilities. SAFETEA-LU requires that transportation agencies conduct "context-sensitive" planning in order to reduce harm to natural and human communities. Because all highways have caused and are causing some level of harm to wildlife movement, arguably transportation agencies should also act to reduce the continuing harm. The continuous nature of the harm through existing and increasing traffic volume should be an easy target for agency and private conservationists needing leverage to encourage the responsible agencies to restore lost ecosystem functions. Public agency staff often would like to conserve and restore natural systems affected by their actions. Therefore, they make useful allies for wildlife biologists and conservationists in planning processes that can support restoration of connectivity. SAFETEA-LU requires that regional transportation plans (RTPs) discuss and identify mitigation actions and sites and that RTP leads must consult with state and local agencies responsible for land use and environmental protection. RTPs are an excellent opportunity for conservation and wildlife biologists to address regional-scale fragmentation by major local roads and highways.

Habitat Conservation Plans (HCPs, under the federal Endangered Species Act [ESA]) and Natural Community Conservation Plans (under the California ESA) are intended to protect threatened and endangered species from the impacts of development activities that result in destruction of habitat for these species. Often this destruction takes the form of habitat loss and fragmentation. Because of this, many plans include consideration of protecting or restoring connectivity for movement of wildlife "targeted" by the plans. Many state and federal agencies look to HCPs to conserve individual species in the face of development. However, Clark and Harvey (2002) found that species covered by conservation plans are significantly more likely to decline, the plans for species less likely to include adaptive management plans, and are revised less often. In addition, Rahn et al. (2006) found that species-specific conservation measures are often lacking in HCPs. In the Riverside Multi-Species HCP, conservationists drafting possible legal challenges found that there were inadequate data on "population status, distribution, and habitat requirements" for some 21 species, nor did the plan provide adequate protection for already degraded riparian, grassland and coastal sage scrub vegetation types. In one case, the RTP associated with the Riverside HCP allowed for an expressway to cut through a reserve identified in the HCP and allows disruption of major landscape connectors. To date, HCPs and NCCPs have not delivered on the promise to reduce or repair landscape and habitat fragmentation.

Local and regional land-use and transportation planning is more and more often conducted under the aegis of "Blueprint planning" funded by the California Department of Transportation. Regional councils of governments (COGs) facilitate the development of joint general plans (municipal) and RTPs. Blueprint planning involves extensive stakeholder input and is supposed to include the available environmental and socio-economic data. Ultimately, these plans are a way to combine regional transportation, conservation, and land-use planning. This makes them ideal for dealing with fragmentation from a more holistic planning viewpoint. Currently, habitat connectivity barely registers on the list of concerns that most Blueprint planners have. However, because stakeholder and resource agency input is considered important to the process, there are opportunities to bring information about connectivity and wildlife movement to bear. Because implementation of these plans is intended to include performance measure monitoring, it will eventually be possible to measure their effectiveness from the point of view of connectivity and wildlife movement.

Infrastructural Approaches

Acquisition of lands is a commonly-proposed approach to protecting so-called "core habitat areas" and re-connecting landscapes for wildlife movement. In theory, areas or parcels can be identified (e.g., using GIS) that are likely to contribute to the protection or repair of lost connections. If these areas are strategically located, it is possible that connectivity could be enhanced or protected for many years. In one such study in the Sierra Nevada, such areas were identified and a network of connected core areas proposed (Shilling et al. 2002). Analysis of the cost of implementing this proposal revealed that such a connected network for the Sierra Nevada would cost around $100 billion for land acquisition (Shilling and Girvetz 2007). This is infeasible with current private and governmental spending priorities. Until priorities change, acquisition of lands in support of connectivity probably is best targeted at very strategic locations. Alternatively, local and state agencies could prohibit zonal and parcel-specific activities that break or threaten landscape connections.

Wildlife crossing of roads and highways is inhibited by characteristics of the infrastructure, traffic, and adjacent land-uses. This inhibition can be remedied for

Figure 2. State highway bridge over stream channel. This under-sized bridge (relative to flows) provides only dry-season passage along riparian areas within an agricultural landscape.

many roadways by constructing under and over-passes, strategic fencing, reducing traffic volumes and speeds, and/or closing roads. The California Department of Transportation (CDOT) is actively pursuing constructed solutions for wildlife crossing. In collaboration with scientists at U.C. Davis, CDOT has developed a guidance manual for agency biologists, planners, and engineers to create wildlife-crossing solutions for California highways. The manual covers approaches that CDOT can use to determine where crossing is inhibited and how wildlife movement can be facilitated. Bridges over stream channels can be retrofitted to permit crossing under the roadway even while the stream is at bank-full (Fig. 2). Retrofitting of existing roads and highways to facilitate wildlife crossing of the right-of-way is one of the cheapest ways to re-connect landscapes that are continuously and without mitigation impacted by highways and traffic.

Evaluating Effectiveness

Trying to repair landscape connections involves experiments in different approaches and investments of energy and limited funds. For both of these reasons and to support steady investments in connectivity solutions, state officials must assess effectiveness of these experiments. This can occur in several ways and at several scales. One approach is to study how often and what kinds of wildlife use infrastructure built for them compared to the goals for the structure. Another approach is to investigate the impact of the repaired connection on wildlife population movement and well-being. These evaluations are best done at both the scale of the wildlife crossing itself and at the landscape scale to evaluate how well the approach works at both scales. Timeframe for effective evaluation is on the order of years, though some wildlife will use the facility immediately and others rarely or never.

Adaptive Management

The process of repairing connections for wildlife and evaluating their effectiveness is best done in the context of adaptive management (AM; Fig. 3). This is a process of planning, acting, learning, and re-planning. By following this cycle, agencies can build on prior ac-

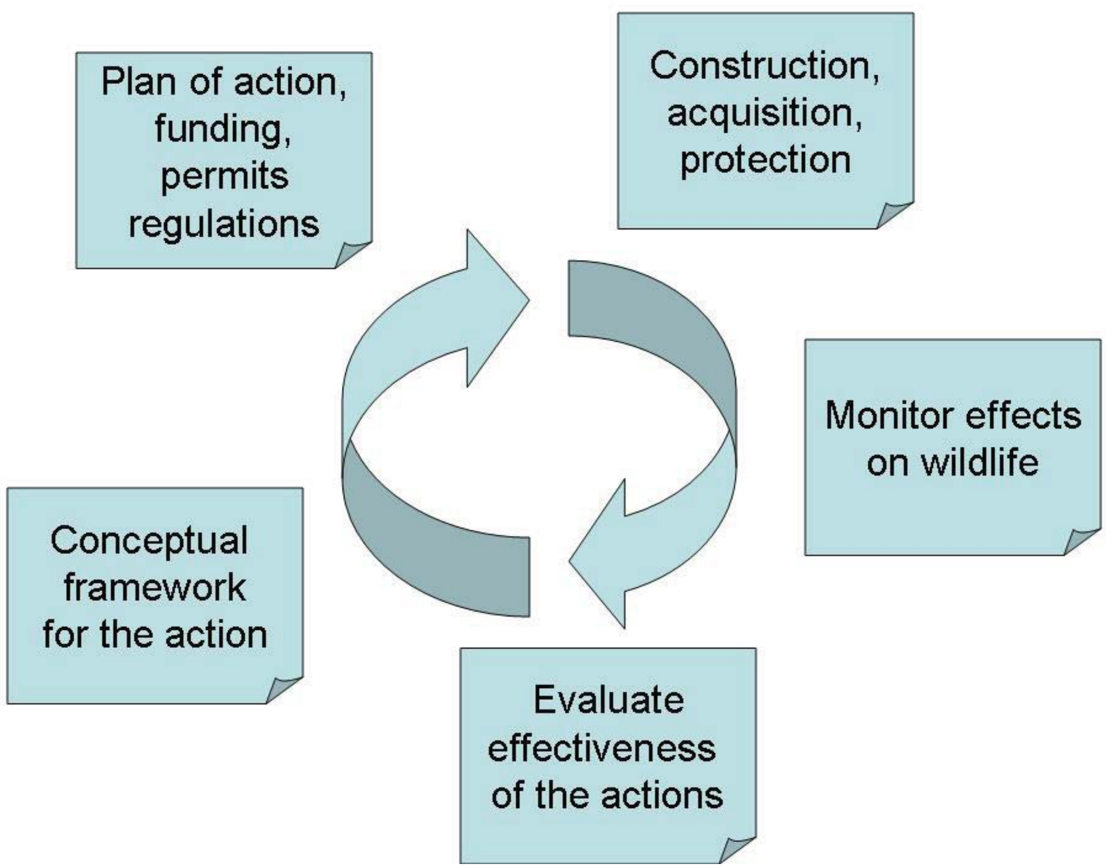

Figure 3. Adaptive management cycle for repairing lost connectivity.

tions and escape criticisms about repeating old mistakes and not monitoring how well wildlife are doing. To effectively carry out AM, however, CDOT, CDFG, USFWS, and others will have to ensure adequate funding is provided to the monitoring component, which often is the weakest link in the process.

THE FUTURE OF RE-CONNECTING CALIFORNIA

Academic scientists and others have evaluated connectivity over the last decade in order to establish a foundation for repairing connections lost to development and protect California's diverse wildlife (Shilling et al. 2002, Thorne et al. 2006, Penrod et al 2006). These studies have often been at the eco-regional scale (e.g., the Central Coast) using a variety of approaches. There is a push currently to evaluate fragmentation and connectivity at local, regional, and statewide scales in order to inform regional and statewide land-use and transportation planning. This effort is based in academic institutions (U.C. Davis, U.C. Berkeley, U.C. San Diego, and others) with critical consultant partners (South Coast Wildlands) and agency partners (CDFG, CDOT). The goals are 1) to protect critical connections already identified in developed regions like Southern California, 2) to describe the wide range of connectivity and threats to connections in rural (e.g., Central Valley) and less-developed (Sierra Nevada) landscapes, and 3) to recommend solutions as part of regional and statewide land-use and transportation planning.

The scientific literature has exploded recently with studies of connectivity and large-scale approaches that states and countries can take to re-connecting landscapes. These studies often depend on a combination of bio-physical and focal species approaches (see above). In California, the plan is to build upon initial regional analyses using this combined approach, to include stakeholder participation and the most contemporary scientific approaches. In urbanized Southern California and the Bay Area, protected areas are surrounded by high-intensity urban and suburban development. In these areas, there are tight restrictions on wildlife movement through identifiable wildlife corridors. Repairing and protecting connectivity in these developed areas consists of heavy investment in the corridors through acquisition and wildlife crossings to increase the possibility of movement among the protected areas. In the agricultural Central Valley, there is ample opportunity to move, but there are few native habitat areas. Repairing and connecting landscapes here will consist of identifying actual and potential core habitat areas suitable for native plant restoration and preserving wildlife movement across major highways (e.g., I-5). In rural and wildland areas of the North and Central Coast, Cascades and Sierra Nevada, and Desert regions, fragmentation tends to consist of diffuse impacts, with the occasional high-intensity use. In these places, it makes less sense to look for wildlife corridors because the vast majority of the landscape is available for some movement. Repairing and protecting connectivity in these areas will consist of dealing with land-use policies that allow diffuse sub-division of lands and low to moderate densities of roads. It will also consist of remediating major and ongoing highway impacts (e.g., I-80).

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Case Study

Herpetofaunal mortality crossing a highway

In one impressive study of wildlife mortality caused by highway traffic (Aresco 2005), over 10,000 individual amphibians and reptiles were found dead over a 2 ½ year period along a 0.6 km stretch of highway. In daily observations, the author found that 44 species of herpetofauna were impacted by the highway and these impacts were only partially mitigated using fencing. Mitigation was effective for turtles, but less effective for species capable of climbing. The highway carried ~20,000 cars/day and bisected migration routes from one lake to another. It was and is comparable to many other highways in the US, suggesting that the impacts may also be comparable.

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