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The Ecology of Rural Roads: Effects, Management, and Research

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SUMMARY

Road networks form the basic transportation system for most of the world's inhabitants, stimulating local and regional economies. Scientific advances in recent years have revealed that this vast, growing, planetary construction boom has been occurring mostly in non-urban environments, and most aggressively in developing frontiers of tropical regions. However, even in highly urbanized countries, road networks consist mostly of roads outside of urban areas. To produce a reliable, comprehensive picture of the global road network, scientists have taken advantage of improvements in mapping technologies, including automated detection from satellite imagery and real-time mapping on the ground. Because the extent of the global road network is increasing at a rapid, unprecedented pace, the pervasive and sometimes dramatic impacts on ecosystems and their services in rural areas will continue. The science of road ecology has emerged to quantify these effects and propose solutions to mitigate the detrimental effects of roads and their traffic. This report explains these effects and examines implications of road ecology research for decisions and actions, including some management practices to help mitigate the negative ecological effects of rural roads.

Some of the major ecological effects of roads in rural landscapes include:

- Destruction of habitat, including fragmentation of plant and animal populations.
- Traffic disturbance, including animal-vehicle collisions that reduce populations and/or habitat quality to the point of causing local extinctions.
- Introduction and establishment of invasive and non-native plants and animals that compete with native flora and fauna.
- Pollutants, including hydrocarbons, salts, nitrates, heavy metals, and pesticides, emitted from vehicles, road surface materials, and associated with dust. These pollutants persist in and change the roadside environment, including aquatic habitats (e.g., near-road streams) and downstream aquatic systems (e.g., estuaries).
- Alteration of hydrology: ditches change water movement and infiltration patterns; road structures affect erosion and sedimentation of streambeds; culverts fragment streams altering movement of aquatic fauna.
- Increased access to remote places that, in turn, enables the collateral destruction of habitats, the degradation of ecosystems, and the loss of biodiversity.

Several strategies exist for mitigating the negative effects of roads in rural landscapes. Road ecology can be applied advantageously in transportation policy, planning, and decision making to reduce the impacts of roads by evaluating development alternatives, including whether to build a road, where to build, as well as how and when to build. Such strategies can be applied at continental, regional, or local scales, contributing to the discussion of tradeoffs within a framework of sustainable development. Strategies for mitigating environmental impacts include configuring roads to avoid destroying ecosystems, installing fences to reduce road mortality, creating safe passages for wildlife under and over roads, controlling traffic during critical times for key species, and following best practices for road construction and maintenance.

Road ecology is a young science that has advanced rapidly in recent years. Thousands of scientific studies have, since the late 1990s, measured various environmental responses to roads and their traffic with the intention of quantifying the extent and magnitude of ecological effects. But, the current challenges to road ecology now involve working with large volumes of data, integrating datasets, and incorporating these data into models. Furthermore, there is a challenge in synthesizing the information across disciplines, for example, combining data on hydrological, chemical, and health effects to understand the depth and range of ecological responses. Therefore, as road ecology matures and addresses these challenges, a much more nuanced and complete understanding of the ecological effects of roads is emerging.

Smaller low-volume rural road systems are not usually as well-mapped or as well-studied as their higher-volume counterparts, yet they constitute the lion's share of the global road network and are at the frontiers where ecological patterns and dynamics strongly influence human activities. Conversely, the characteristics of the road network in these far-flung locations (e.g., how well connected they are) have implications for the future of rural communities and the landscapes in which they are embedded. While these roads offer many benefits to people living in remote rural areas, grappling with rural road impacts and addressing them with solutions for mitigating their negative ecological effects is a priority for road ecology. The community of road ecology scientists is, in cooperation with land managers and decision makers, committed to identifying the problems and evaluating potential solutions to better manage road-related ecological impacts in rural landscapes.

INTRODUCTION

From space, vast webs of human settlements can be seen spanning the planet, and they are almost entirely connected by roads. People have ventured and will continue to go wherever there is a road, and its adjacent land use has likely changed. Roads bring the promise of increased access to natural resources and, in turn, to markets and trade for producers. A road by itself is but a disturbed piece of earth, but when connected with other roads, it becomes a link in a broader network. Road networks can open entire regions to trade, economic development, and new ideas and uses, and people often see roads as signs of progress, so it is no wonder that developing the road network is central to many socio-economic development objectives. Yet roads alter and degrade the scenic and natural value of the landscapes they fragment, undermining potential sources of economic development. Recent independent efforts to map the global road network have resulted in estimates of the global extent of roads that range between 9.1 and 64.3 million kilometers depending on which road map data were used.* Even the most conservative estimate shows sufficient roadway to encircle the Earth's equator over 200 times. This vast human production signifies the vital role transportation infrastructure plays in local and regional economies, but it also constitutes an enormous human footprint with the potential for immense unintended ecological impacts.

Roads indelibly alter landscapes through both space and time. Long after the initial rationale for building a road is gone, its effects can linger, sometimes for centuries; for all intents and purposes, roads permanently change a landscape. For example, remnants of the ancient road systems of southwestern Asia, such as the Royal Road of Persia that linked ancient Susa

*The Global Roads Open Access Data Set (gROADS) v1 (1980-2010) reported 9.1 million km of roads worldwide, while the US Central Intelligence Agency "World Factbook" reported 64.3 million km in 2013.

and Persepolis (Iran) with Sardis (Turkey) in 500 BCE, are still evident today. The most enduring elements of these roads include infrastructure like the historic "Ten-Eyed Bridge" near Diyarbakir, Turkey, crossing the Tigris River. The specific land use influences of such ancient roads are hard to ascertain today, but the Greek historian Herodotus described how they facilitated communications in the Persian Empire, implying swifter and more effective territorial administration. While the evidence of highways may remain, remote unpaved roads tend to be ephemeral. Temporary logging roads, for example, might be used for months or years, but can be rendered practically invisible within a few years or decades.

BOX 1.
WHAT IS A RURAL ROAD?

Most observant travelers would be able to tell whether the road they are traveling on is in the countryside, a suburb, or a town, but the answer to this general question of road definition is not so easy. There is no globally accepted definition of a rural road. The simplest definition is a road in a rural area, which begs the question: What is a rural area?

According to the US Department of Transportation, rural areas are "outside of the FHWA-approved adjusted Census boundaries of small urban and urbanized areas." Based on the measure of population density used by the US Bureau of Census, over 96 percent of the conterminous US is rural. The US Federal Highway Administration reported that, in 2018, about 2.9 million miles (4.7 million km) of public roads that receive federal highway funding in the US (including D.C., Alaska, Hawaii and US Territories) were rural—roughly 70 percent of the public road system; of that, 1.27 million miles (2 million km), were unpaved rural roads, roughly 30 percent of all public roads in the US.

Roads are often classified by function—for example, as limited-access highways, arterials, collectors, and local roads. Rural roads can also be defined in terms of the landscapes they bisect, whether farms, forests, mountains, or deserts. Roads have also been classified by the connecting roles they play; rural roads have been defined as connecting farms to villages and villages to markets.

A related term is "low-volume roads", roads with a low average annual daily traffic volume, often considered less than 1000 vehicles per day. More than 80 percent of all US roads are low volume, a proportion that is consistent for many national road networks.

While these roads form the critical infrastructure for people living in rural areas, level of use does not always equate to whether a road is "rural." There are many low-volume roads in urbanized areas, and conversely, there are many higher-volume roads that traverse rural areas. For example, the Trans-Canada Highway system traverses remote rural areas of Canada carrying high volumes of passenger vehicle and truck traffic. Furthermore, a volume of 1000 vehicles per day can have high impacts. Even traffic volumes of 300 vehicles per day can impact some species.

However they are defined, rural roads are both paved and unpaved. Unpaved roads can be dirt roads or covered by some surfacing material, such as gravel or other stone aggregate. Unimproved roads are dirt roads without surfacing material and no regular maintenance.

For the purpose of this paper, we focus attention on those rural roads that tend to:

1) be farther from cultural centers;

2) be less regularly maintained; and

3) provide the first critical links between population centers and remote land uses such as mining and forestry.

The vast majority of the global road network comprises roads in rural areas, is predominantly low in traffic volume, and mostly unpaved, yet by comparison to highways and paved roads with high traffic volumes, these rural roads have generally been neglected in ecological research (Box 1). The longest rural road networks are in Russia, the United States of America (USA), Australia, China, Brazil, and India, ranging from about 287 thousand kilometers in India to about 517 thousand kilometers in Russia (Figure 1). Countries in Central and Southern Africa tend to have higher proportions of rural versus urban roads than countries in the Americas and Europe, regardless of size. However, with only a few exceptions in smaller, highly urbanized countries like Belgium, the rural proportion of the road network predominates. In the US, where

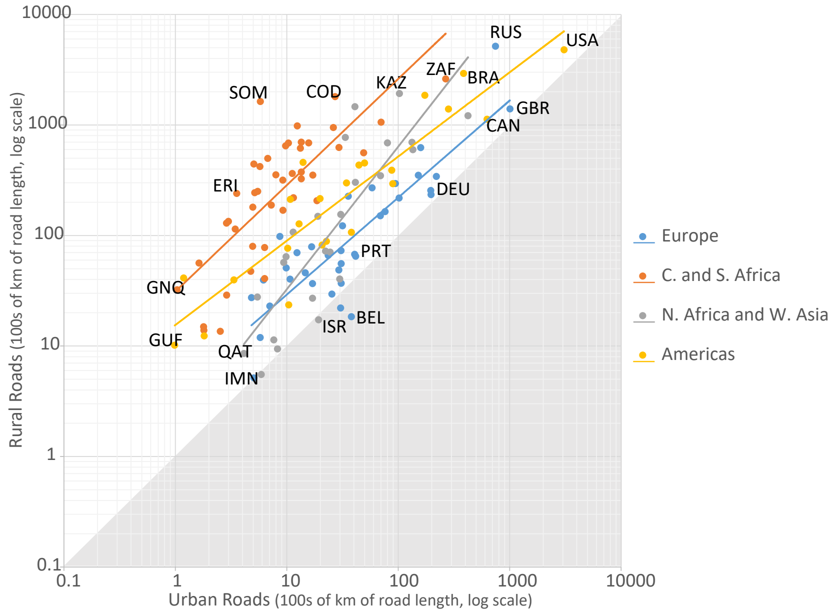

Figure 1. *Urban vs. rural road network extents for various countries, categorized by major geographic regions for Europe, Central and Southern Africa, North Africa and Western Asia, and the Americas, including trend lines for each. Global urban areas were used to differentiate urban vs. rural roads in the global roads data set. In most countries, rural roads predominate the entire network. Country abbreviations: Belgium – BEL, Brazil – BRA, Canada – CAN, Democratic Republic of the Congo – COD, Eritrea – ERI, Germany – DEU, United Kingdom – GBR, Equatorial Guinea – GNQ, French Guyana – GUF, Isle of Man – IMN, Israel – ISR, Kazakhstan – KAZ, Portugal – PRT, Qatar – QAT, Russia – RUS, Somalia – SOM, United States of America – USA, South Africa – ZAF. Data source: Center for International Earth Science Information Network (CIESIN)/ Columbia University, and Information Technology Outreach Services (ITOS)/ University of Georgia. 2013. Global Roads Open Access Data Set, Version 1 (gROADSv1). Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC).*

road networks are well documented, most public rural roads are labeled as "local" and "minor collector roads" (Figure 2). It is not surprising that most roads in the US are relatively small with low volumes, and this pattern likely describes rural road networks everywhere.

The global road network reveals a level of human access to the planet that is both extensive and immediate, and in a matter of years new roads and accompanying land use changes appear in tandem to completely transform landscapes (Figure 3). In 2016, an analysis of global roads indicated that, while roadless areas (at least 1 km away from a road) covered 80% of the Earth's terrestrial surface, more than half of these areas are patches of less then 1 square kilometer. Whether driven by resource extraction, colonization, or long-distance trade, building a road through a previously isolated region opens landscapes for further development. The impacts of roads on biodiversity are pervasive; indeed, the cumulative effects of roads have been called the "sleeping giant" of environmental biology.

In this report, we address the following questions about rural roads: What is the state of research into rural road ecology, and what additional research would help land managers mitigate the impacts of rural roads? What are the major effects of rural roads affecting the environment in most bioclimatic zones? What policies and practices can land managers use in planning and building rural roads to minimize ecological impacts? In short, how can we better consider the tradeoffs between social and economic benefits and ecological effects associated with rural road development and use?

The dramatic expansion of scientific research in road ecology in recent decades enables us to answer these questions, and we do so by using a conceptual framework that describes road ecology as central to three "spheres" of road development and use: understanding the ecological effects of roads (effects); informing decisions about transportation, mitigation, and landscape plans (decisions); and helping to enact road design, construction, and use strategies (actions; Figure 4). However, most road ecology research is not designed with a particular focus on rural roads. Therefore, throughout this paper, we ask: "What does the research we review mean in the context of rural roads?" We start with a description of road ecology, including the rise and development of this branch of scientific research. We then describe some major ecological effects of rural roads, including biogeochemical effects, hydrologic and atmospheric effects, effects on invasive species, and effects on wildlife, which are supported by case studies. We follow this with an examination of current national

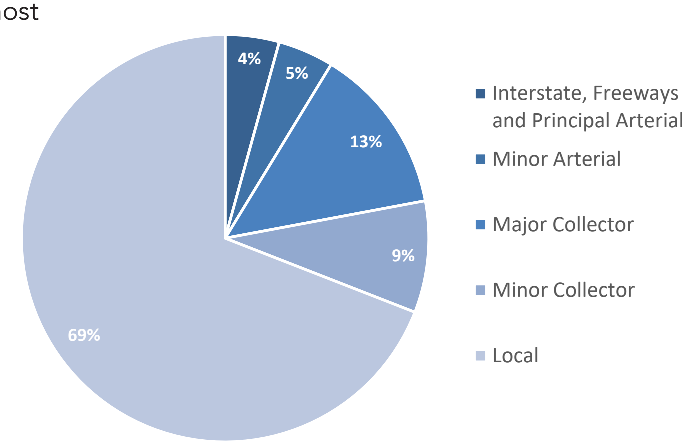

Figure 2. *Proportion of public roads by category in the US in 2018. Local roads and minor collectors constitute almost 80% of all public rural roads in the US, classified by the US Department of Transportation. This proportion has remained steady since 1980. No data has been collected for private rural roads across the entire nation.*

and international policies for rural roads, where such policies have been developed. We describe best management and mitigation practices (BMPs) for the planning, design, and use of rural roads, including a list of BMPs for each of these phases of development. We wrap up the report by discussing current research needs, particularly with respect to rural road networks, and we provide conclusions and recommendations.

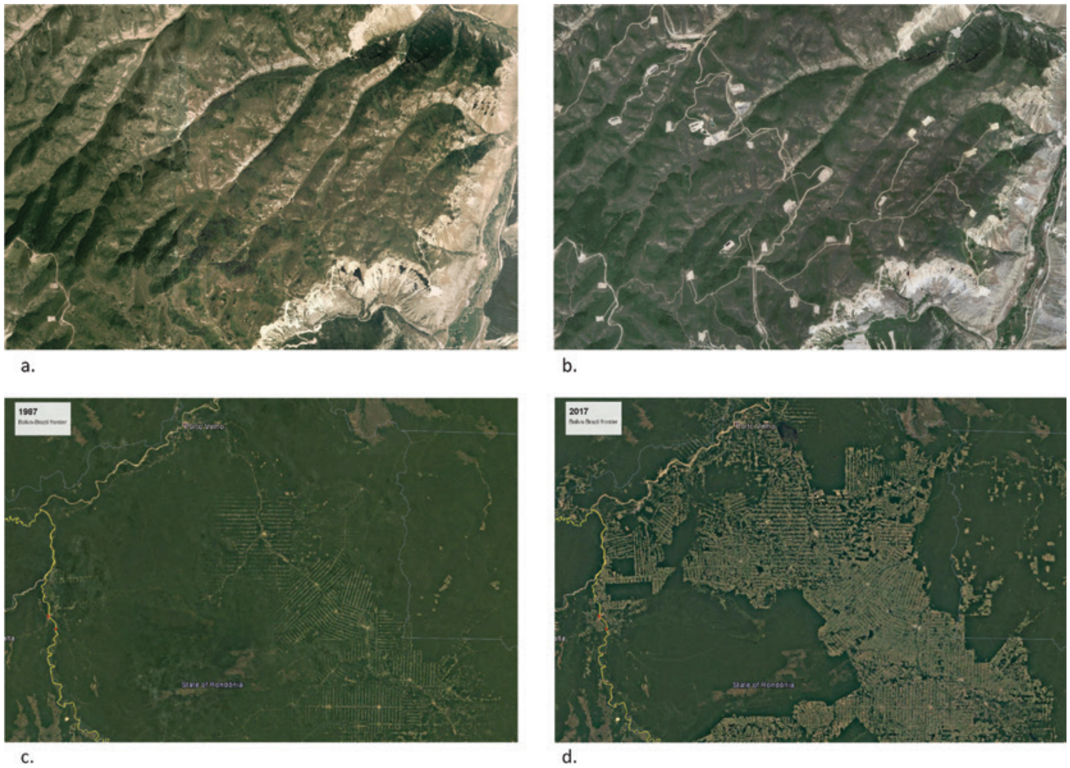

Figure 3. *Imagery showing road networks in rural areas of Colorado, US, in 2005 (a) and 2014 (b), and Rondônia, Brazil, in 1987 (c) and 2017 (d). Colorado road development patterns are indicative of gas and petroleum extraction, while Rondônia configurations show typical "fish bone" patterns of colonization and agricultural expansion. (Imagery provided by Google Earth: USDA, Farm Service Administration, National Agriculture Imagery Program; Landsat / Copernicus).*

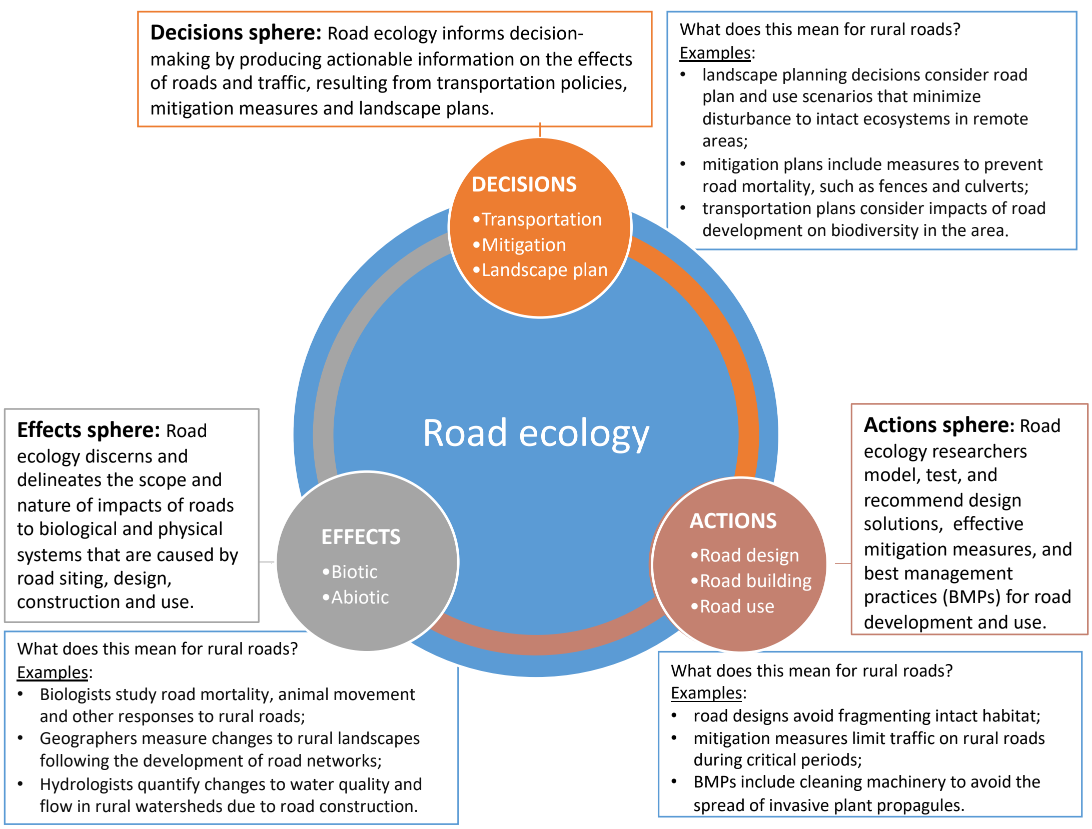

Figure 4. *Graphic showing the relationship of Road Ecology to spheres of decisions, actions, and effects. These relationships form a conceptual framework illustrating the associations of road ecology science and practice with various stages of road system planning, development, and use.*

THE RISE OF ROAD ECOLOGY

As people came to understand that roads have environmental impacts, a field of research emerged in the early 20th century bringing attention to their detrimental effects. As roads extended across landscapes to accommodate motorized vehicles, biologists noted the inevitable collisions of animals with vehicles. Initial studies were rudimentary, usually designed to help improve highway safety by reducing vehicle collisions with animals. Scientists systematically counted the numbers, species, and locations of vehicle-killed animals.

In 1981, the German vegetation ecologist Heinz Ellenberg and his colleagues first used the term road ecology *(Straßenökologie)* in German, providing a distinctive name to this field of research. Their study emphasized the effects of emissions, road salt, noise, and changes in climatic conditions on vegetation and wildlife and they warned of further fragmentation of landscapes by road construction. They also provided recommendations for reducing the use of herbicides, for the choice of roadside vegetation based on ecological principles, for reducing roadkill, and for reclaiming roads that are no longer needed. Richard T. T. Forman, a US landscape ecologist, and his colleagues translated the term in 1998 for an editorial in Landscape Ecology, in which they referred to the 1981 study by Ellenberg and others. Use of the term in English expanded further following publication in 2003 of the book *Road Ecology: Science and Solutions*.

Road-specific animal mortality studies still comprise most road ecology research; discrete and site specific, the corresponding research entails a well-defined, limited scope of work. Such studies provide useful information on the species affected as well as the timing and locations of collisions. They continue to be instrumental in planning and designing mitigation measures along high-volume roads in rural landscapes. In addition, the rise of citizen science, engaging the public in scientific projects, coupled with web-based data reporting in the last decade has also benefitted the compilation of road-kill events worldwide. Free download smartphone applications illustrate the growing potential to obtain large and geographically extensive datasets with minor costs.

Although traditional animal mortality studies contribute to our understanding of animal-vehicle collisions, they do not explain how strongly collisions with vehicles affect wildlife populations. To do so requires a deeper understanding of animal populations, such as their longevity and reproduction, and broader ecosystem responses of factors like vegetation, which in turn, affect wildlife. Consequently, a growing number of studies have collected information about seasonal, annual, and decadal responses to roads, for example, providing information about animal movements and their relationships to traffic patterns. One such study observed that Rocky Mountain elk avoid trails with all-terrain vehicles but not those with equestrian traffic (Case Study 1). Remote animal tracking, using tags that record or transmit animal positions, along with genetic and observational studies, also reveal the effects of roads on animal behavior.

Other site-specific road-effect studies, such as those examining changes to light, microclimate, dust, pollutants, hydrology, non-native species, and other measurable effects have vastly increased our understanding of how roads affect ecosystem properties and processes, along with local flora and fauna. In fact, the number of road ecology studies has mushroomed over the last two decades (Figure 5), with the number of publications increasing by over 400% since 1996. While this progress is impressive, further research is needed to link road management effects to the behavior of animals over broad temporal and

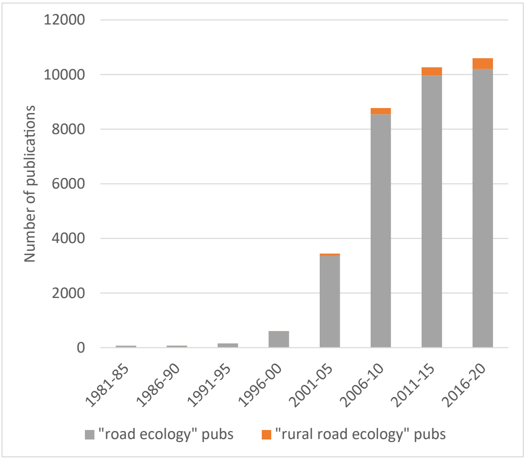

Figure 5. *The volume of English language publications with key words "road" and "ecology" has mushroomed since the publication in 1998 of the first influential papers coining the term "road ecology". The height of the bar indicates the number of publications discovered by a key word search of the EBSCOhost "Environment Complete" database. Although many road ecology studies are executed in rural areas, the proportion of publications explicitly including the term "rural" occurred in about 3% of studies, shown here in orange.*

spatial scales. For example, studies that evaluate the effectiveness of mitigation measures often suffer from limited scope, weak study design, and lack of funding. A recent analysis of mitigation studies noted that incorporating a minimum study duration of four years and comparing conditions before and after the mitigation measure is put in place would improve the evaluation of effectiveness.

TABLE 1. THE EFFECTS OF ROADS AND TRAFFIC ON LANDSCAPES AND ECOSYSTEMS

THEME	ENVIRONMENTAL EFFECTS AT OR NEAR ROADWAYS
Landscape Elements	• Land occupation for road surface and shoulders • Soil compaction or sealing of soil surface • Alterations to geomorphology (e.g. cuts, embankments, dams, stabilization of slopes) • Removal and alteration of vegetation
Local Climate	• Modification of temperature conditions (e.g., heating of road surface; increased variability in temperature) • Accumulation of cold air at embankments of roads • Modification of humidity conditions (e.g., lower moisture content in the air due to higher solar radiation and reduced vegetation; stagnant moisture on road shoulders due to soil compaction) • Modification of light conditions • Modification of wind conditions (e.g., due to aisles in forests) • Formation of steep micro-climatic gradients which act as barriers
Emissions	• Vehicle exhaust, pollutants, fertilizing substances leading to eutrophication (excess nutrients in water bodies lead to excessive plant growth) • Dust and particles emissions (e.g., abrasion from tires and brake linings) • Oil, fuel, etc. (e.g., as a result of traffic accidents) • Road salt and de-icing compounds in higher latitudes and elevations • Noise, depending on vehicular traffic and atmospheric conditions • Visual stimuli; lighting from passing traffic, infrastructure and road associated activities
Water	• Drainage, faster removal of stormwater, preventing groundwater infiltration • Modification of surface watercourses • Changes to groundwater flows • Water pollution from deposition of emmissions near roads
Flora/Fauna	• Death of animals caused by vehicle collisions (partially due to animals' attraction to roads) • Formation of a road-effect zone with lower population densities near roads • Higher levels of disturbance and stress, loss of refuges • Fragmentation, reduction, and loss of habitat for many species; creation of new habitat for a few species • Breaking up of animal and plant populations, reduction of biodiversity, loss of species, and extinction • Genetic isolation, inbreeding effects and increased genetic drift, and interruption of the processes of evolutionary development • Disruption of meta-population dynamics, shifts in sex ratios, changes in population structure, and community composition (e.g., predation release through the elimination of large predators) • Barrier effect, filter effect to animal movement (reduced connectivity) • Disruption of seasonal migration pathways, impediment of dispersal, reduced recolonization of empty habitats • Disruption of access to resources that are dispersed across the landscape, modifications of food availability and diet composition (e.g., reduced food availability for bats due to cold-air buildups along road embankments at night) • Increased intrusion and distribution of invasive species • Creation of pathways facilitating the spread of infectious diseases

Source: Jaeger, J. (2003): II-5.3 Landschaftszerschneidung [II-5.3 Landscape dissection]. - In: Konold, W., R.Böcker, U. Hampicke (Eds.) (1999ff.): Handbuch Naturschutz und Landschaftspflege. *11th fascicle11/2003. Ecomed-Verlag, Landsberg, Germany. 30 pp. [handbook arcle]*
Note: Effects of construction sites such as soil excavation and deposition, vibrations, and acoustic and visual disturbances are not included.

EFFECTS OF RURAL ROADS ON ECOSYSTEMS

Many countries value and protect their rural open spaces as essential to their national character. In her Geographical History of America, Gertrude Stein wrote: "In the United States there is more space where nobody is than where anybody is. That is what makes America what it is." But, in the U.S. and around the world, even the most empty spaces "where nobody is" have roads, and even lightly used roads can have profound cumulative impacts on the environment—through the chemicals they shed, through the watersheds they transect, through the invasive species they introduce, and through the ways they affect wildlife (Table 1). Of particular note are the ecological effects of roads in tropical rainforests, which are substantially different than the effects of roads in other ecoregions. While the ecological impacts described below are not focused on any one ecoregion, the climatic, biological and economic conditions in tropical rainforests exacerbate many of the effects. For example, in the moist tropics, intense rainfall can cause severe erosion of roads resulting in gully formation that not only destroys the road but impacts aquatic ecosystems downstream where the sediment is deposited.

Biogeochemical Effects

Biogeochemical effects include the family of effects caused when chemical elements or substances are transferred to the environment. Roads have biogeochemical impacts when chemicals related to the roads themselves or to the vehicles traveling on them are washed off or deposited along gradients away from the road. Many of these gradients are relatively short (< 200 meters) and most of the deposition is within the first 5-10 meters, but sometimes chemicals are transported much farther by waterways. These chemicals include heavy metals such as zinc (Zn), copper (Cu), cadmium (Cd), lead (Pb), chromium (Cr), manganese (Mn), and nickel (Ni) from engine, tire, and brake wear; salts such as sodium chloride (NaCl) and calcium chloride (CaCl) from deicing and dust control; gases such as nitrogen oxides (NO_x) and ammonia (NH_3) from exhaust emissions; and hydrocarbons such as polycyclic aromatic hydrocarbons (PAHs). For example, in a comparison of European studies, researchers found higher than background median levels of Cd, Cr, Cu, Ni, Pb, and Zn in the 0-5 m area closest to the road, some of which were strongly correlated with lower soil pH. However, these studies were focused primarily on roads with high traffic volumes, with higher volume roads having higher variability and median concentrations of metals. Therefore, it could be expected that metal concentrations would be lower along lower-volume roads. The impact of chemicals in the environment varies, but many cannot be broken down by micro-organisms. Therefore, their persistent, long-term toxicity to plants, animals and people is of concern.

The road itself is a source of dust, sediments, and particulates, which have biogeochemical effects. Surface aggregates (mixtures of crushed rock or gravel) are frequently used on dirt and gravel roads to create a safe surface for driving. Both through direct runoff and through the creation of dust, the effects of the aggregate may be felt far beyond the road itself, altering soil pH and affecting vegetation. For example, higher pH of soil adjacent to limestone-aggregate surfaced roads likely helped invasive Japanese stiltgrass become established along roadsides (Figure 6).

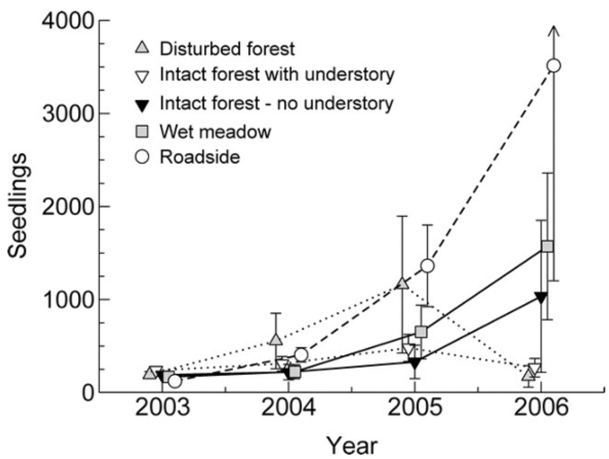

Figure 6. *Seedling recruitment of Japanese stiltgrass (Microstegium vimineum) was higher in patches adjacent to roads which were associated with higher levels of pH in the soil. (Source: Nord, Andrea N., David A. Mortensen, and Emily S. J. Rauschert. 2010. Environmental Factors Influence Early Population Growth of Japanese Stiltgrass [Microstegium vimineum].* Invasive Plant Science and Management *3:17-25.)*

Numerous studies have examined the heavy metals associated with roads, measuring their content in storm water runoff and in roadside soils. For example, research on roadsides of the Qinghai-Tibet Plateau of China found that the concentration of heavy metals in roadside soils depended on traffic density, varied with terrain and wind, and decreased exponentially with distance from the road, usually reaching background levels within 50 meters. In Australia, scientists found further contamination when road sediments and dust containing heavy metals washed into nearby streams, resulting in higher heavy metal concentrations in stream sediments. In another study, researchers discovered higher concentrations of heavy metals in the first 10 meters of roadside grasses, contaminating potential food sources for livestock and wildlife.

Other chemicals associated with vehicles, such as emissions and organic pollutants, also increase in quantity with more traffic. Incomplete fuel combustion, along with tire wear and road surface abrasion, are sources of these chemicals. Nitrogen (NO_x and NH_3) emitted in vehicle exhaust lands on the road and washes into local streams where it impacts the availability of plant nutrients in soils, affects nearby plant species composition, and contributes to pollution in aquatic systems, potentially at much greater distances. For most rural areas, roads with low traffic volumes are often free of noxious roadside emissions. However, for some rural roads, such as those associated with active mines or wells which can experience periodic heavy traffic by trucks, such contaminants are a problem, and require attention and mitigation.

Road managers apply chemicals (e.g., salt) to roads to maintain safe driving conditions, to control dust, and in cold climates to melt ice and snow. A substantial proportion of road salt – 20-63% in one Swedish study – washes off the road and is deposited nearby. Numerous studies describe the environmental effects of road salt, but the impact varies from place to place depending on local factors such as temperature and precipitation, topography, road drainage, and the amount of salt applied. In addition to physically damaging leaves, road salt also inhibits plant growth by changing osmotic stress which reduces their ability to absorb water. Road salt dissolves in water and filters into the soil, where it changes the structure of the soil, decreasing permeability and aeration, altering soil chemistry, and increasing soil pH. Surface runoff carries dissolved salt into nearby lakes and rivers where it increases the sodium and chloride concentrations. Additives to road salt are toxic to many species of plants and animals living in these aquatic ecosystems and can alter aquatic food webs. Below the surface, groundwater laden with road salt has contaminated drinking water supplies. Road salt is corrosive to concrete and metal structures, and it degrades bridge and road infrastructure, liberating and increasing the mobility of heavy metals.

Hydrologic and Atmospheric Effects

Roads change the flow of air and water, and these changes affect the environment. In rural areas, roadways and traffic interact with watersheds and airsheds, causing a variety of effects originating at the road and extending into the surrounding air and landscape, sometimes for hundreds of meters. As described previously, the chemicals associated with roads and their traffic combine with the action of wind and water to extend biogeochemical impacts up to 50 meters away from the road edge, or even much further, depending on terrain and prevailing winds.

Road surfaces and drainage systems affect the movement of surface and subsurface water across the landscape, altering aquatic systems locally and regionally. The road's semi- or impermeable surface area and storm water drainage systems act as conduits to move water off of the road surface as quickly as possible — water that would otherwise infiltrate to replenish groundwater stores and to be used by plants and released back into the atmosphere through evapotranspiration. Quickly channeling water to streams and other water bodies results in higher peak flows and associated flooding. Moving water quickly into road drainage ditches, which occupy a relatively small area compared to the entire road surface, creates wetter soil conditions in and near the ditch, especially evident in semi-arid and arid environments where wetland species take advantage of the increased water availability and plant growth is more luxuriant. Erosion from unpaved roads in agricultural and forested areas, used primarily for moving farm and forestry machinery as well as harvested goods, causes sedimentation downstream. The fine sediments produced from roadsides reduce water clarity, change the way water flows, and increases water temperatures, in turn changing aquatic habitat and making smaller rural streams less habitable to aquatic species like trout and salmon which require cold, clear streams with gravel substrates. Watersheds with higher road densities experience more sediment and debris flows where excavated road fill erodes or slides into nearby streams. Road networks that dissect rural headwaters may affect the resilience of aquatic plant and animal communities due to changes to stream networks and the intensity of flood peaks caused by roads.

Where roads intersect drainage networks or run parallel to rivers in valleys, associated bridges, culverts, and roadbeds alter the flow of water and sediment that maintain river habitats, thereby fragmenting and degrading floodplain ecosystems and reducing the benefits of riparian buffer zones. In low-relief areas, such as the Amazon Basin or the Southeastern US, bridges and culverts constrain stream flow, leading to increased velocity that scours stream beds. Additionally, in these low-relief areas, roads on causeways interrupt the sheet flow of water across large areas, causing wetter conditions upstream of roads and drier conditions downstream. This is the case for the Tamiami Trail (US 41) which bisects the Everglades in South Florida, and where, for the last century, these types of changes have, in turn, altered key ecological processes, including fire patterns, nutrient flows, and animal movements. Recently, broad plans to restore the Everglades include ongoing modifications to the Tamiami Trail to restore water flow and ecological connectivity by constructing elevated roads. Where terrain is more rugged, as in mountainous regions of the world, roads are more likely to run parallel to stream and river channels in valleys. There, the roads can form a barrier between the stream channel and floodplain areas running parallel to the stream, preventing water from moving into these typically flooded areas, and altering historical riparian flooding patterns. Roads and their traffic affect the local atmosphere creating a microclimate that dissipates with distance from the road. By displacing vegetation with bare ground or pavement, roads alter the temperature, humidity, amount of incoming solar radiation, light reflectance, and wind speed of the immediate area. As most roads are more open and built-up compared to their surroundings, their microclimates tend to be hotter during the day (cooler at night), drier, brighter, and windier than adjacent areas. Specific conditions vary according to region, season, time of day, and how a road is designed. For example, along an unpaved road in the Central Brazilian Amazon, tree transpiration rates have been higher adjacent to the road than farther away, a consequence of higher air turbulence closer to the road. In addition, this "edge effect" extended further from the road in the dry season than the wet season. While the effects of roads on microclimates may be significant locally, their cumulative effects at broader scales are still unclear. For example, we do not know how microclimatic changes caused by road networks affect soil health, forest production, and biodiversity at regional and landscape scales over time.

While roads themselves are structural features that alter the flow of water and air, the movement of vehicles along roads raises dust, which impacts air quality. Traffic on rural roads is generally light, and many roads in rural areas are unpaved. "Fugitive dust" from traffic on unpaved roads has a range of impacts on health and ecology, especially within the first 20 meters of the road. This fine particulate matter: causes respiratory health problems; makes snow near roads less reflective and causes it to melt sooner; reduces plant productivity by coating leaves; and provides surfaces to which pollutants stick and eventually deposit downwind or downstream.

Effects on Invasive Species

An association between roads and invasive species is well-established and documented. The overall density of roads is associated with the presence of invasive species, and the prevalence of non-native species is generally higher along roads than away from them (Figure 7). Roads create more favorable habitat for invasive species by providing light gaps, dispersal corridors, and reduced competition. In some cases, exotic species, deliberately planted along roadsides to stabilize soil, add to the number of invasive plants along roads.

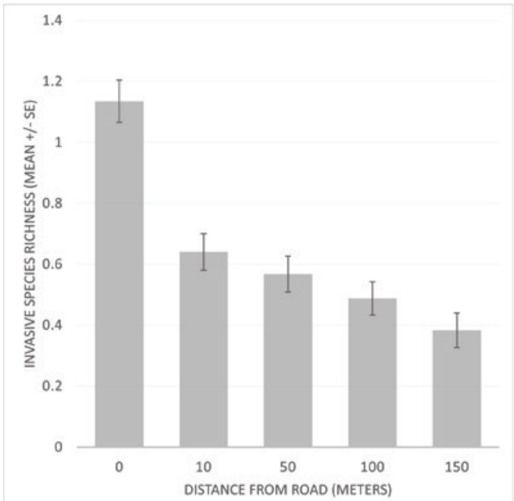

Figure 7. *Richness of invasive species declined with distance from the road, a common outcome of many road ecology/ invasive plant studies. The results shown are from data published in a study by Mortensen, D.A., Rauschert, E.S.J., Nord, A.N., and Jones, B.P. 2009. Forest Roads Facilitate the Spread of Invasive Plants,* Journal of Invasive Plant Science and Management *2: 191-199.*

Plant seeds attach to surfaces and tires of cars, trucks, and equipment used for periodic road maintenance, which means that invasive plant species tend to disperse quickly along rural roads. For example, scotch broom *(Cytisus scoparius)*, once planted to stabilize soils along roads in the western US, now proliferates along roadsides. It outcompetes native vegetation and is now considered invasive (Figure 8).

Figure 8. *Scotch broom in an Oregon landscape, after spreading from a nearby road. Photo: Eric Coombs, Oregon Department of Agriculture).*

Bugwood.org

Most rural road networks are unpaved, and the question of whether or not paving makes a difference to the spread of invasive species has been addressed in a few studies. One study on ragweed (*Ambrosia* spp.) abundance found that it spread and established more readily near paved roads than near unpaved roads. For paved roads, studies generally find higher invasive plant biomass adjacent to roads versus further away; this pattern is less pronounced in unpaved roads. These studies suggest that paving a rural road enhances the spread of some invasive species. However, all rural road networks provide access into remote areas creating opportunities for repeated introductions of these species, contributing to their proliferation.

Although studies about the connections between roads and invasive species have focused mainly on plants, roads also influence the dispersal and redistribution of non-native animals and pathogens. In the southeastern US, red imported fire ants *(Solenopsis invicta)* are commonly found in roadside habitats. Invasive cane toads *(Rhinella marina)* in Australia disperse along roadsides—the higher the road density, the greater the cane toad populations. In the US, invasive insects such as emerald ash borer *(Agrilus planipennis)* and non-native pathogens such as root rot in cedars are spread by vehicles traveling along rural roads. Less directly, when people build roads through remote areas, infectious diseases (e.g., diarrheal pathogens) spread more readily when changes to the environment, that are related to roads, combine to create conditions for increased transmission. These conditions include altered watershed drainage patterns, more intensive land uses with increased human-wildlife contact, and denser human populations accompanied by inadequate sanitation infrastructure.

Effects on Wildlife

Roads affect wildlife in many ways, acting directly when they fragment populations, and indirectly, when they induce changes in animal behavior. The four main mechanisms by which roads affect wildlife populations include:

(i) decreasing habitat area, fragmenting the remaining area, and reducing habitat quality in adjacent areas;

(ii) increasing mortality caused by vehicle collisions;

(iii) reducing landscape connectivity because roads act as barriers (e.g., some animals avoid roads and do not cross them) and sometimes interrupting seasonal migration routes; and

(iv) subdividing populations into smaller and more vulnerable sub-populations.

To appreciate how these four mechanisms affect wildlife, we need to recognize that some of them influence wildlife immediately and others act over longer time periods. The effect of habitat loss is almost immediate, reduced habitat quality and traffic mortality may take longer, and reduced connectivity longer still. Road systems also affect wildlife at different scales, from the individual to local areas where many individuals of the same species form a group (or population), to regions where multiple populations of this species live. In addition, previously described impacts of roads (e.g., biogeochemical and hydrologic) can also impact wildlife. Although less common, roadsides sometimes provide habitat for certain species, and as mentioned roads are vectors for invasive species.

Habitat fragmentation caused by the presence of roads with traffic increases the edge-to-interior ratio of habitat patches, which in turn, can impair species that need large blocks of habitat or networks of patches linked by movement corridors. A key problem with fragmenting habitat is that it can isolate groups of animals, preventing them from breeding, reducing gene flow, and diminishing their chances for persistence. The use of genetics in road ecology, while so far underutilized, holds much promise for helping researchers understand the effects of roads on wildlife populations. For example, in Australia researchers found that, after analyzing genetic data from squirrel gliders *(Petaurus norfolcensis)*, a road crossing structure effectively restored gene flow in the population within five years of its construction at a point where they had previously observed a barrier to gene flow.

Roads act as barriers, but they can also act as filters, because some individuals or species avoid them, while others do not. For example, prairie voles *(Microtus ochrogaster)* and cotton rats *(Sigmodon hispidus)* in the US were unable to cross roads three meters wide. Road avoidance behavior varies widely by species and depends on the animal's physical traits, the individual's choices, its ability to move in the landscape, and its population density. The timing of traffic conditions is clearly a factor in determining whether an individual will cross a road. For example, bobcats *(Lynx rufus*) and coyotes *(Canis latrans)* observed in Southern California crossed roads to reach patches within their home ranges at times when traffic levels were low. Furthermore, road characteristics matter to many of the animals that cross them. Research on pumas *(Puma concolor)*, a wide-ranging gregarious species, showed that the cats crossed unimproved dirt roads more frequently than improved or hard-surfaced roads. Measuring how animals respond to roads and their traffic is an important area of research in road ecology. In the western US, several studies have examined animal movements using telemetry to monitor behavior relative to roads and traffic. During annual migrations, mule deer *(Odocoileus hemionus)* experience higher rates of mortality at road crossings; Rocky Mountain elk *(Cervus canadensis nelsoni)* avoid all-terrain vehicles (Case Study 1). In the same region, Gunnison sage-grouse *(Centrocercus minimus)* fitted with GPS tracking devices avoided roads; the study mapped their movements in relation to passing vehicles and known breeding grounds, or lek sites (Case Study 2, Figure 9).

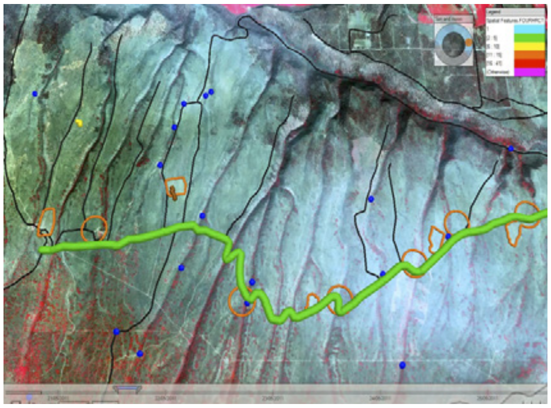

Figure 9. *Still image from video (linked below) demonstrating simultaneous tracking of vehicle traffic in relation to the movement of two individual sage grouses. The false color image is an aerial photograph of a landscape in Colorado, with roads shown as black lines, known lek sites outlined in orange, and potential lek sites shown as blue dots. The green line indicates a pulse of monitored road traffic.*

One unresolved debate in road ecology focuses on the relative harm to wildlife of fencing roads versus leaving roads unfenced or using other technologies such as wildlife warning reflectors, intended to interrupt animals' movement onto roads at night when vehicles are present. Research has clarified tradeoffs among them as well as the reasons why particular approaches may be appropriate in different situations (e.g., small rural roads versus high-traffic roads). Interrupting animal movement with fences reduces collisions with cars but fences also interfere with habitat connectivity. The debate focuses on the question under what conditions the isolating effects caused by connectivity interruptions due to animal crossing barriers are worse than the effects of animal mortality caused by vehicle collisions. Those who think of situations in which the latter are worse point out the immediate consequences of mortality, and that, ideally, fences should be used in conjunction with wildlife passages to ameliorate the barrier effect. Furthermore, they emphasize that if roads are not fenced, then animal-vehicle collisions continue, driving populations into decline, regardless of whether the populations are connected across a road. Wildlife warning reflectors, while very cost efficient, are debated because past studies have not demonstrated that they lower animal-vehicle collisions. However, a recent analysis of this work suggested that the research did not fully account for confounding factors, and, as the research was carried out using a variety of methods, further standardized research approaches are needed to assess their effectiveness. The relative importance of one potential solution over another depends to a large extent on the behavior of the focal species in question, the amount of traffic on the road and the land management status of the road area (private or public). In rural areas, low traffic volumes (less than 300 vehicles per day) may not justify the expense of implementing road crossing structures and fencing; however, even traffic volumes of 300 vehicles per day are significant for some species. This can easily be the case in times of amphibian migrations across a rural road, even with rather low traffic volumes. Even then, strategies such as temporary road closures during critical periods may be more suitable for rural roads. Research aimed at resolving these questions for smaller rural roads has yet to be fully developed.

Figure 10. *Bear crossing a road in Montana, US. Photo: Doug Ouren, US Geological Survey.*

In some areas, logging roads have left a legacy of unmanaged human access to remote regions, with severe consequences for wildlife populations. This problem has been particularly marked in tropical regions where roads provide access to poachers of large mammals. In Central Africa, roads have been a major driver of elephant poaching and consequent decline in their populations; and planned road development projects may reduce the economic benefits from ecotourism. Large carnivores are particularly susceptible to the effects of roads in remote areas (Figure 10) because these animals tend to avoid roads and areas near roads, and they are thus affected by the reduced area of viable habitat. As with elephants, carnivores suffer increased levels of poaching where roads enable poachers to gain access. A recent study modeled carnivore population viability across the globe, revealing that numerous carnivores are particularly exposed to the negative effects of roads. The models, which combined road density and available habitat with species traits (e.g., population growth rates) showed that many species, including Iberian lynx *(Lynx pardinus)*, Japanese badger *(Meles anakuma)*, and Japanese marten *(Martes melampus)*, are highly exposed to roads and may be expected to become very rare or disappear in the coming decades.

Even though for most native species roads present challenges to individuals and populations, some species benefit from roads. For example, power and fence lines that often accompany roads provide new perches for a variety of raptors. Carrion-feeding species may benefit from animal-vehicle collisions by eating the remains. However, this dynamic is a double-edged sword when they risk getting hit by vehicles themselves. Results from a recent study that modeled animal population responses to changing road densities showed that, for animals attracted to resources from a road, increasing road densities would not necessarily increase their population. A compounding effect occurs when a species' abundance increases in areas with higher road densities due to the lack of predators, also known as "predation release". This is the situation in the case of white-tailed deer *(Odocoileus virginianus)* in the eastern US. There, the lack of large carnivores has allowed deer populations to increase, in turn detrimentally affecting the mix and rejuvenation of trees and understory plants that make up the forests where they live and increasing the frequency and costs of deer-vehicle collisions.

In summary, the effects of roads tend to be generally negative for wildlife, acting as barriers or filters, reducing available habitat, and causing death from vehicle collisions. These impacts to wildlife reverberate over space, from local to regional scales, and over time, from immediate to generational scales. This combination of time and space means that roads can profoundly affect the ability of wildlife at the individual level, the population level, and, ultimately, as a species, to persist.

Landscape and Regional Effects

As networks, the ecological effects of roads extend across broad areas and cause cumulative effects that are poorly described by analyzing one road segment. Taking a landscape perspective of the effects of roads allows scientists to approach the problem more holistically. This perspective requires researchers to pay attention to the broader aspects of the road systems they study like the adjacent land uses, traffic characteristics, and overall road network connections and spatial arrangement. These considerations form the basis for an ecological road network theory, which draws from the fields of landscape ecology and transportation geography.

Landscape ecology can be used to quantify various ecological aspects of landscapes and regions. To measure the cumulative effects of road network development over time, researchers use numerous indicators that describe how the landscape is changing, such as the sizes and shapes of roadless patches and the amount of roadless area. For example, a study in northern Wisconsin, US, over a 50-year period of development, showed that the size of roadless patches decreased and the shape of these patches became more regular as road density increased. Likewise, in the Congo Basin, researchers developed a statistical tool to measure roadless space and found that, over time, logging concession areas all lost roadless space, while national parks did not. Their study, however, was limited to protected areas and logging concessions, so we still lack information about most of the landscape which does not fall into either of those categories. Given that road systems fragment the landscape, indicators that measure levels of connectivity at landscape and regional scales are useful for modeling, measuring, and describing the interactions between roads and the landscape. Even simple measurements of road density and distance from roads can help bracket expected levels of ecological effects in a given region.

As roads develop across regions, they cause changes in land cover, but also appear as a result of changing land uses. Over the last few decades, studies focused on tropical deforestation have found repeatedly that road development is one of the key factors in the predictable patterns of land transformation. In many frontier situations, road development is linked with mining and forestry. Where land is poorly monitored and legal protections are virtually non-existent, roads built for legitimate reasons, such as providing access to national ports of entry, become conduits for illicit activities, like illegal mining, timber extraction, and poaching. Illegal mining, for example, occurs when government controls over an area are weak and individuals or groups informally mine without permits, leading to changes in settlement patterns and land use in remote areas. Eventually, as transportation costs decline, the region becomes more attractive to farmers and ranchers, and the forests or grasslands give way to agriculture, extending hundreds of meters from the road. Consequently, more roads are built to provide more access to more intensively used land, and ultimately, the entire landscape is transformed. In the Amazon Basin, where deforestation has long been observed, a combination of political and economic policies has been driving these destructive transformations.

DECISIONS AND ACTIONS: POLICY AND BEST PRACTICES FOR RURAL ROADS

As road ecology research continues to develop, transportation policies increasingly incorporate principles of landscape ecology and adaptive management into guidelines for road development and management. Resources about road ecology, from scientific papers that provide reflective questions (Figure 11), to handbooks and guides, are increasingly available to transportation planners and managers. However, much of the recently gained knowledge about the cumulative effects of roads on plant and animal populations has yet to be incorporated into decisions and translated into actions, especially those effects occurring at broader spatial and temporal scales. Because transportation policies exist at national, subnational, and local levels, incorporating knowledge from road ecology into policy and practice requires engagement with many different institutions. Where those institutions lack sufficient resources or capacity to function effectively, the job is that much harder. In tropical and subtropical countries, large rural road networks combine with biodiversity hotspots to produce some of the most strategic opportunities for "high-return" mitigation, where relatively simple measures to avoid or correct the negative impacts of roads can make a big difference for conservation. However, it is often the case that these are places where governance operates with limited capacity, and centralized institutions are far-removed from the road-building frontier. Therefore, road ecology adoption in planning and management

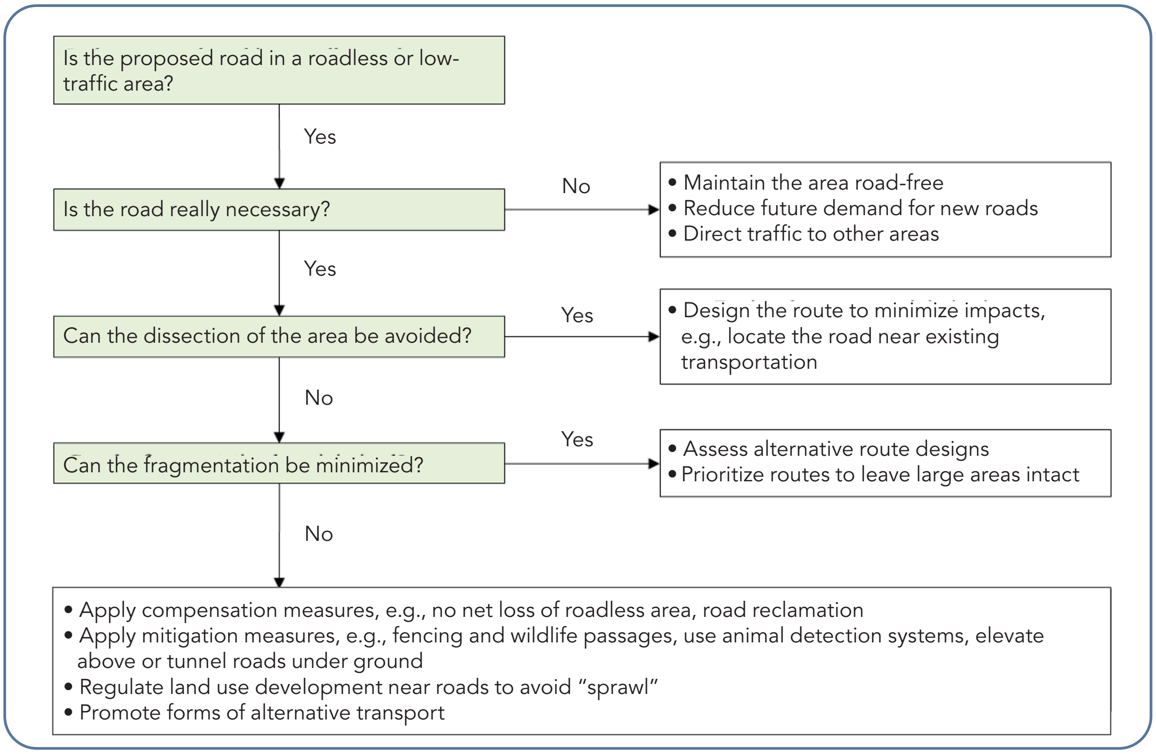

Figure 11. *Four main questions to ask when planning a road project in roadless or low-traffic areas. (Source: adapted from Selva* et al. *2015. "Why Keep Areas Road-Free? The Importance of Roadless Areas" in eds R. van der Ree, D. J. Smith, and C. Grilo.* Handbook of Road Ecology. *John Wiley & Sons)*

policies is less well developed. This situation underscores the importance of the implementation of ecological "best practices" for road development in these regions.

Policy Approaches in the United States and the European Union

The most notable examples of transportation and land policy taking advantage of road ecology science are in industrialized countries, including recent changes to transportation policies in the United States (US) and the European Union (EU). Historically, rural transportation management policies failed to consider broader, landscape-scale dynamics related to cumulative ecological effects of rural road network development and use. Typical project-based, fine-scale decision processes gradually impact and cumulatively alter landscapes, i.e., a "death by a thousand cuts." Policy solutions that incorporate broad-scale landscape ecological approaches are found to be more effective in managing the spatially diffuse effects of roads on regional- or continental-scale ecosystem processes. Solutions may, for example, prioritize conservation areas where the development of roads would fundamentally alter regional ecological processes, such as animal migrations or basin-wide flood patterns. Incorporating environmental standards in the planning, design, development, and maintenance of roads is squarely in the public's interest, providing for consideration of the long-term effects of rural road systems on natural resources and biodiversity. Most transportation development agencies maintain some level of environmental standards in their policies and procedures. In one case, the US Federal Highway Administration and its Sustainable Highways Initiative provide numerous publications and tools to aid transportation planners in the development of highways and roads. However, in the US, a variety of governmental agencies at the state, county, and municipal levels are also responsible for rural road policy and can enforce their own rules, creating sometimes complex multi-layered decision processes. Globally, the extent to which the standards used by transportation departments have effectively integrated road ecology solutions is an open question, as no comprehensive review of such standards exists. Therefore, this is an area of potentially valuable research.

The US Forest Service (USFS) manages extensive areas of land including thousands of kilometers of low-volume rural roads. In the late 1990s, due to the increasing use of USFS lands for recreation, insufficient funding available to maintain the existing road system, and a growing body of scientific evidence about the ecological impacts of roads, the USFS turned its attention to road management policy. In 2001 the USFS published its "Roadless Area Conservation Rule" that fundamentally changed its longstanding approach to managing the roughly 58.5 million acres (236.7 thousand km^2) of inventoried roadless areas, or one-third of the nation's federal system of national forests and grasslands. Rather than managing road development via independent land management plans for each national forest, the rule encompasses the whole system of USFS-managed land and prohibits most road construction and reconstruction, as well as timber harvest in inventoried roadless areas. More than a decade of litigation put in question the rule's implementation, and during that period, a state-led petition process resulted in two state rules (Colorado and Idaho) with greater flexibility than the original rule's prohibitions. Most recently, a rule was adopted for the Tongass National Forest (Alaska) exempting it from the 2001 Roadless Rule. But as of 2012, the rule still stands as the law of the land for most of the states.**

Another USFS policy that mitigates road impacts and stands to reduce mounting

**On October 1, 2012 the Supreme Court declined to review the Tenth Circuit Court of Appeals ruling to uphold the original 2001 rule. The rule does not necessarily apply in Idaho and Colorado where state-specific rules were finalized in 2008 and 2012, respectively, under the state petition process. On October 29, 2020, the USDA adopted a specific rule exempting the Tongass National Forest from the 2001 Roadless Rule (www.federalregister.gov/d/2020-23984). For more information: https://www.fs.usda.gov/roadmain/roadless/home.

costs related to road maintenance was the 2005 Travel Management Rule. It curbs unrestricted motorized access by designating when and where motorized vehicle use is permitted. In the past, unbounded motorized use within national forests resulted in the proliferation of user-created routes—up to tens of thousands of kilometers across the country, though no definitive inventory exists. In sum, the rule provides a way to find opportunities to reduce the total number and length of open roads—not insignificant given that USFS manages more kilometers of roads than any other entity in the nation.

In the EU, few initiatives specifically restrict road development in natural areas or aim to protect roadless or low-traffic areas. The EU conservation policy is mostly based on the Natura 2000 network. It consists of "Special Protection Areas" and "Special Areas of Conservation" following the "Birds Directive" and "Habitats Directive", respectively (79/409/EEC and 92/43/EEC). However, a large proportion of Natura 2000 sites are either located in proximity to major transportation infrastructures or may potentially be affected by the future development of the European transport network since the level of the standards of protection are often too weak to avoid further habitat fragmentation, as various recent examples have shown. Many legal instruments in Europe aim to protect wildlife habitat connectivity, ecosystem processes, or ecosystem integrity; but none currently considers roadless or low-traffic areas as a conservation target.

In recent years, policy in the EU has shifted from species and habitat protection to approaches encompassing broader ecological conservation measures. For example, Germany's 2009 Federal Nature Conservation Act established that "traffic and energy infrastructure and similar projects shall be integrated so that fragmentation and consumption of the landscape as well as ecological impairment is avoided or reduced to a minimum." Germany is the first European country where data on the distribution and size of low-traffic areas have become available. To support landscape assessments, the German Federal Agency for Nature Conservation developed the concept of areas unfragmented by traffic (UAT). The UATs are areas greater than 100 km^2 that are free of higher volume roads (>1000 vehicles/day – a volume much higher than the ecological thresholds described earlier), railroads, human settlements, airports and channels. The first inventory in 2008 identified about 9 million ha of UATs in Germany, of which only a quarter are protected under European Directives. Most low-traffic areas (75%) are outside of the Natura 2000 network and thus remain without protection.

Another example of a policy designed to address road impacts in a relatively large-scale, holistic way is aimed to reduce fragmentation in the Swiss Alps. The "Alpine Article" in the Swiss Federal constitution (Article 84) limits the capacity of trans-alpine road transportation (i.e. "must not be increased") and demands a shift to railway transportation for goods. The 2003 Carpathian Convention signed by seven countries addresses regulations of traffic impacts and development and encourages the parties to develop sustainable transportation policies. However, neither the EU nor most national laws currently recognize the significance of areas with low levels of fragmentation by roads in their conservation policies. Even this choice example of a policy that considers the sustainability of transportation faces a challenge incorporating scientific understanding about the enormity of global road network impacts. To focus attention on this gap in legal frameworks, participants at the 2014 international conference of the Infrastructure and Ecology Network Europe (IENE 2014) unequivocally called for a "pan-European strategy to protect roadless areas" that explicitly incorporates these areas "as conservation targets in national and European policy and legislation."

Best Practices for Rural Road Development

Guidelines, specific strategies, and design solutions for rural road networks, to which we refer as a body of "best management practices" (BMPs; Box 2), are in development and codified to varying degrees in different places. Institutions charged with creating transportation plans are increasingly cognizant of emerging best management practices in the planning, design, construction, and maintenance of both new and existing roads.

Road network development occurs in phases beginning with planning and design, then construction, and lastly, maintenance, during which ecological solutions can be included. This process is typical with new roads and reinitiated wherever existing road networks evolve to meet the changing socio-economic demands of a region. Sometimes roads are finally decommissioned and, increasingly, such roads undergo a process of ecological restoration. Going forward, decisions to decommission certain roads, and not to build others, will likely include assessments of the projected impacts of climate change compounding the ecological effects of a road and its traffic. While direct ecological impacts are clearly associated with the construction and maintenance phases, the planning and design phase may offer the best, most cost-effective opportunities for avoiding or minimizing deleterious ecological effects. This is particularly true in rural areas, where road development, existence, and use are most likely to alter or affect ecosystems.

Asking the right questions at the planning and design stage (Figure 11) can help guide the decision and planning processes to evaluate alternative solutions for road development, avoiding unnecessarily negative effects. If road-related impacts cannot be avoided then they must be addressed through mitigation, which can sometimes be expensive. Roadway designs to mitigate habitat fragmentation effects on wildlife are becoming more common, as shown in the 2016 NOVA documentary "Wild Ways," produced by WGBH Boston (www.pbs.org/wgbh/nova). In protected areas, land management agencies have greater authority to enact traffic management plans that limit the traffic on roads and can do so temporarily or permanently. Monitoring traffic patterns in protected areas is a critical step in being able to evaluate not only the effectiveness of public traffic management plans, but also the traffic associated with land management itself, which, as noted in Case Study 3, may also contribute to road-related disturbances.

RESEARCH NEEDS FOR ROAD ECOLOGY

Road ecology research is reaching new levels of maturity with increased focus at international levels. It is not uncommon to see attention given to major impacts caused by highways bisecting landscapes, especially where the presence of endangered species causes notable concern. The consequences of this growth in road ecology research and synthesis are already being seen in the ways organizations develop and manage roads in the protected areas they manage. For example, public lands agencies may decommission or temporarily close roads, limiting motorized access to some areas to protect sensitive species and landscapes. Although researchers have collected increasingly broad information on how roads affect animal behavior and populations, many unanswered questions remain. Chief among them are uncertainties about the complex interactions among roads and their use, animal behavior and wildlife abundance, and landscapes modified by roads. Researchers seek answers about how these factors impact genetic pools, species assemblages, and evolutionary processes of animals over many decades. For example, scientific research evaluating the ecological effects of permanent and seasonal road closure, and the cumulative benefits of such actions is rare. Suitable study designs that can address these research needs, especially considering climate change scenarios, are required.

Data and Analysis Needs for Rural Road Ecology

Data about road networks and their use by traffic, along with analytic methods to measure, simulate, and evaluate ecological responses to roads are the building blocks of road ecology. Data streams of these types are often high volume, and the methods to analyze them require specialized knowledge,

BOX 2. ECOLOGICAL BEST MANAGEMENT PRACTICES FOR MITIGATING THE IMPACTS OF ROADS

Best management practices (BMPs) are strategies and actions that aim to provide balanced solutions to complex environmental problems. Typically, these involve direct measures taken to ameliorate potentially harmful activities as they occur, such as using hay bales or textile fences along drainage channels to lessen the pollution of waterways from sediment eroding during construction. However, avoiding ecological effects by restricting, limiting, or prohibiting road development is also part of the BMP toolkit. This includes the option of avoiding road construction projects with insufficient budgets to follow through with design, construction, and management practices that incorporate mitigation measures and their maintenance. Mitigation typically consists of a three-pronged approach to address environmental impacts, including avoidance, minimization, and compensation. This framework provides a useful way to think about BMPs for road networks. A common example of mitigation for the effects of roads on wildlife entails the design and construction of crossing structures to connect habitat patches and facilitate the safe passage of animals. Structures include both those aboveground, via overpasses and fencing, and belowground, via specially designed culverts or tunnel passages. Other designs for mitigating road impacts on wildlife include wildlife crossing detection devices, perch deterrents on power lines and fences, and restoration of areas significantly altered by roads and their use.

The report "Low-Volume Road Engineering: Best Management Practices Field Guide," by G. Keller and J. Sherar, provides an excellent overview for BMPs for roads typically encountered in rural environments, and following their "recommended practices" offers the best opportunity to protect ecosystems in these cases. Likewise, the American Association of State Highway and Transportation Officials (AASHTO) Standing Committee on the Environment offers guidelines for transportation planners and designers to assess environmental impacts of road development projects. The following is a bulleted list of BMPs applicable to different phases of road development taken from field guides and other sources. These are not exhaustive but complement the recommended practices described in the above-mentioned sources. While not explicitly listed for each phase, following environmental BMPs published by organizations like AASHTO as a minimum specification for road projects at every stage would provide the best available solution for managing road related ecological impacts.

1) PLANNING AND DESIGN PHASE BMPS

Environmental considerations should be included from the early stages of road project planning and design, supporting decisions about if and where new roads will be built, or existing roads redeveloped. Thorough assessments should consider the project context and use ecological planning and sustainable design principles to minimize negative environmental effects.

Consider the context.

- Identify quantitative levels of fragmentation and/or indices of roadless areas in the surrounding landscape (e.g., road density).
- Synchronize with wider regional ecological objectives for the protection of regional ecosystem dynamics, such as the preservation and management of low-traffic or roadless areas.
- Maintain wildlife habitat and wildlife movement corridors, identify and maintain existing corridor networks.
- Avoid or minimize habitat fragmentation caused by roads.
- Preserve intact roadless areas through careful planning and design, for example, by "bundling" roads and thereby clustering road impacts.

Use ecological planning methods to support decisions in locating and aligning new roads or in improving or realigning existing roads.

- Conduct inventories of biological and cultural resources in the proposed rights-of-way and those that might be affected in the surrounding landscape.
- Conduct mapping to accurately establish a baseline inventory of existing roads.
- Analyze existing and potential wildlife-traffic conflicts and water and air quality problems.
- Consider alternative scenarios that minimize ecological effects.

along with innovation and creativity to combine them with rigorous clarity.

The breakneck speed at which remote sensing and geospatial analysis have advanced has brought us much closer than we were a decade ago to having accurate road maps of appropriate extent that are essential if we are to quantify the ecological effects of roads. For studies of large areas, promising new mapping technologies use such methods as automated detection and "crowd sourcing" to collect and provide freely available fine scale road data at unprecedented spatial extents

- Develop and incorporate "traffic calming" approaches that identify rural areas where road network traffic is reduced by re-routing traffic to trunk roads, possibly downgrading or closing some existing roads.
- Where impacts are anticipated, establish goals for their mitigation.

Use sustainable landscape design and engineering principles for roadway design. In addition to published BMPs, consider the following:

- Align roads to minimize disruptions, such as to surface and subsurface water flows and fish movement.
- Buffer areas adjacent to roads for the management of storm water runoff and the attenuation of dust and noise.
- Reduce road width wherever possible to minimize habitat disturbance.
- Plant native plants for road edge stabilization and maintenance, avoiding the introduction of invasive plants.
- Slow and manage the flow of storm water runoff using swales and retention basins that prevent scouring and the direct introduction of road silt and pollutants into natural drainage systems.
- Incorporate best options for structures that facilitate safe wildlife crossings such as fish passages, fences, and under- or overpasses.
- Use design and engineering standards for sight distance with the goal of reducing animal-vehicle collisions, such as reducing the design speed.
- Minimize the generation of noise and dust by specifying low impact surfacing materials.
- Reduce glare and excessive light with low-glare energy efficient lighting standards and reflective paints.

2) CONSTRUCTION PHASE BMPS

When road construction occurs, land is transformed into transportation links. Careful planning and management of the construction process can help to limit the negative effects of road development. High quality construction standards include planning and mitigating for construction-related impacts. In addition to published BMPs for road construction, consider the following:

- Limit construction areas to clearly identified zones within the right-of-way.
- In remote areas, limit poaching by road-building crews by providing sufficient provisions and discouraging poaching.
- Incorporate erosion control measures such as silt fences.
- Clean road building equipment and machinery prior to entering a new area to avoid the spread of invasive species as "hitch-hikers".
- Incorporate safety management plans, including chemical spill protection and response measures.
- Minimize the generation of dust.
- Remove and properly dispose of waste from the construction zone.

3) MAINTENANCE AND MANAGEMENT PHASE BMPS

Roadway maintenance and management activities cause chronic disturbances to the roadside environment. Management BMPs focus on minimizing negative effects and adapting to changing circumstances. In addition to published BMPs for environmental mitigation, consider the following road maintenance BMPs:

- After establishing thoughtful baselines, monitor the effects of roads on wildlife, plant communities, and water and air quality, periodically evaluating the effectiveness of mitigation measures, e.g., monitoring if roadkill hotspots have shifted.
- Adapt management solutions to meet environmental goals as conditions vary.
- Establish road and roadside management specifications and maintenance schedules that are minimally disruptive to wildlife and natural processes, avoiding the use of pollutants wherever possible.
- Consider temporary or permanent road closures for critical areas and during critical times (e.g., breeding or migration seasons) to minimize wildlife-traffic conflicts and reduce animal-vehicle collisions.

(e.g., www.openstreetmap.org). Although it is still difficult to find complete, well-documented, accurate maps of rural road networks, the road-mapping "terrain" has been shifting dramatically in recent years. The establishment of global navigation satellite systems, combined with the proliferation of low-cost cellular service in rural areas around the world is making it possible to locate remote roads with adequate precision, accelerating the road mapping process. In addition, high performance computing systems implementing "artificial intelligence" systems are becoming very adept at automatically detecting roads in satellite images of ever-increasing clarity. In the past, insightful map librarians or cartographers sometimes archived datasets, but until recently archiving was not a standard (or even common) part of the research process. As with map creation, archiving historical datasets has become much more tractable with the conversion to digital mapping systems. For example, regularly archived snapshots of the global roads dataset from 2013 onward, produced by the OpenStreetMap Foundation's community of mappers, are now freely available to download from their data repository (www.openstreetmap.org).

Although these developments will undoubtedly support road ecology science, there are still significant challenges related to the quality and accuracy of road datasets that limit road ecology research, often in the very places where this research could be most impactful, such as poorly mapped forests or savannahs, where the effects of road construction on endangered wildlife are most severe. The reliability of road datasets varies from one place to the next, and with few clear standards or systematic assessments about their accuracy, spatially explicit measurements of uncertainty are unavailable. This situation is especially problematic in regions where mapping resources are scarce, which are often less populated areas and development frontiers, and where the need for road ecology studies may be most critical. These issues stymie road ecology researchers who commonly use historic and current road network maps as "before and after" datasets to model environmental changes. It remains difficult for researchers to acquire accurate road maps that portray smaller, low-volume rural roads at more than one point in time. This is due to the high costs of creating such datasets, combined with the lack of universal mapping standards that address issues of scale, accuracy, and road features.

Road network maps provide critical spatial information about location, but they do not readily provide critical information about traffic patterns. Traffic pattern data, maintained by local and regional transportation authorities, are more common in urban and suburban areas, and on toll roads, where traffic is monitored and measured. Studies documenting traffic patterns along rural roads are virtually nonexistent. Since so much of the impact of rural roads depends on the volume and timing of traffic, understanding the actual patterns of road use through time in these regions is critical to assessing their impacts.

Whereas road network maps and traffic data help us to understand the pressures of roads on surrounding ecosystems, measurements of air, water, soils, plants, and animals provide the critical information about responses. Live animal responses are often measured using telemetry, with GPS tracking devices that allow for indirect and near constant monitoring of animal movements relative to vehicles and traffic. The volume of data produced by such studies is substantial, and the data analysis requirements are, likewise, formidable. However, while statistical expertise is in high demand and hard to come by, the availability of statistical modeling tools to support ecologists in animal movement studies is developing quickly.

Research Gaps and Frontiers in Rural Road Ecology

An important gap in road ecology research is understanding the cumulative effects of rural roads and their traffic on ecosystems and landscapes. Roedenbeck *et al.* (2007) pose five research questions that aim to identify the effects of roads on wildlife population persistence at the landscape scale (Figure 12). They further outline an experimental framework for increasing the strength of conclusions about causes and effects in road ecology research, both to advance knowledge in the field, and for applying that knowledge to real-world planning of transportation systems. They point out the need for well-designed experiments that document effects before and after the development of roads or the installation of mitigation measures, and that include control sites for comparing purposeful observations and data collection across road and non-road areas that are otherwise similar (so-called BACI design).

Another gap in road ecology research is understanding the thresholds in road density, at which wildlife populations decline, and the response times of wildlife populations to habitat loss, increased mortality, and reduced connectivity. There is a time lag between road construction and wildlife population responses. After this time lag, the population is smaller and more vulnerable to extinction. The overall response may take several decades and is likely to depend on the road network density. The response times for most species are not known, although related to the species' generation time, and this realization is important for environmental impact assessment (EIA) because it implies that the decline and loss of populations could continue for several decades after road construction. The term 'extinction debt' denotes the number of populations that will go extinct because of changes that have already occurred in the landscape. Thus, EIA and landscape conservation planning should consider the effects of land use on animal survival and movement and the associated response times. Related to this is the question of our ability to reverse potential negative impacts during this lag period. Reversing the impacts is a major effort that involves not only stopping the impacts, but also restoring the ecosystem. While we have some ideas about population lag times and extinction debts based on current research, this is an important area of research where new approaches coupling genetics, mapping, and computer modeling can improve those estimates and help inform our understanding about cumulative effects of roads and the potential efficacy of mitigation measures.

An explicit evaluation of road network configuration strategies that modify road density versus strategies that modify traffic volumes in real landscapes is an urgent research priority. For example, is it less harmful to wildlife to accommodate a growth in vehicle numbers by upgrading existing roads to carry higher volumes of traffic or to increase the total length of roads in the network? Under either strategy, road mortality rates increase, but it is far from intuitive which one results in lower increase in mortality, lower habitat loss, lower reduction in connectivity, etc. Such questions could be asked of any one of the many effects described earlier, such as hydrologic and atmospheric consequences. Ecological modelling can make important contributions to address such landscape-scale questions since experimental approaches are not usually feasible at this scale.

QUESTION 1

Under what circumstances do roads affect population persistence?

QUESTION 2

What is the relative importance of road effects vs. other impacts on population persistence?

QUESTION 3

Under what circumstances can road effects be mitigated?

QUESTION 4

What is the relative importance of the different mechanisms by which roads affect population persistence?

QUESTION 5

Under what circumstances do road networks affect population persistence at the landscape scale?

Figure 12. *Five questions to identify relative effects of roads on wildlife population persistence. (Source: Roedenbeck, I. A., Fahrig, L., Findlay, C. S., Houlahan, J. E., Jaeger, J. A. G., Klar, N., Kramer-Schadt, S. and Grift van der, E. A. (2007) 'The Rauischholzhausen agenda for road ecology',* Ecology and Society, *12 (1):11.*

Building on the understanding that road ecology has produced about issues such as population fragmentation, and the chemical and physical effects of roads and their traffic, road ecology research is now at a stage where it needs comprehensive, integrated approaches with coordinated efforts between ecologists and transportation agencies to produce more useful research results with greater scientific merit. Harmonizing the spatial and temporal scales of the many kinds of data involved in road ecology research is a key priority for moving forward. This includes matching the scales of road building and projected traffic volumes with questions about species distributions, air and water quality, and animal behavior and mortality. Toward this end, a data collection protocol that is executable and useful for rural transportation agencies, while meeting scientific rigor for ecological studies, would help advance the practical application of road ecology. Such a protocol that identifies minimum data collection standards, with a common set of terms for rural road networks, could help standardize the datasets across broad regions so that effects of roads can be properly compared and assessed over time.

CONCLUSIONS AND RECOMMENDATIONS

Road networks and their traffic result in multiple long-term ecological effects as demonstrated in numerous detailed scientific studies. While people need roads for access to resources, roads have far-reaching consequences for the ecology of rural landscapes. The construction and maintenance of road networks are among the most expensive human land use investments; moreover, the full costs of road development are much higher, because they include the value of "externalities"— lost or diminished ecosystem services such as biodiversity and water filtration. The challenge is to plan and manage rural landscapes to minimize the need for rural roads and to mitigate their adverse effects on rural ecosystems, a goal which underpins regional economies.

Road ecology provides a useful ontology of road systems for describing the scope and nature of road impacts; modeling, designing, and testing strategies and solutions for impact mitigation; and producing actionable information for making decisions about road networks (Figure 4). Before building a road, it is vital to take into consideration both the short- and long-term ecological effects of that road, including its use and its maintenance and to consider alternatives, including the no-road option. Mitigation measures might appear costly, but over time they can be the most cost-effective approach to road development through the savings they bring by preventing accidents and sustaining ecosystem services. During the planning and design phases, adopting road development approaches that aim to sustain the full value and the long-term ecological integrity of those places will likely better serve the interests of people living in rural landscapes.

For roads already in use, mitigation measures can be implemented to retrofit and reduce road impacts. They include design, management, and maintenance solutions. Such measures have the benefit of reducing effects of roads on ecological systems while also improving the safety of existing roads and reducing the unnecessary damages caused by animal-vehicle collisions. For higher-trafficked and paved rural roads, design solutions can be considered to manage wildlife movement, such as fencing and crossing structures, and to manage storm water runoff, such as retention basins. For lightly traveled rural roads, mitigation measures could begin with surveying the potentially affected ecosystems and taxa, along with the locations, conditions, and use of existing roads, to assess their impact, and use the information to propose targeted, creative management approaches for impact reduction. Research suggests that customizing the application of mitigation to the needs of species that are negatively affected by roads is most effective. Examples of such approaches might include measures to limit access to certain places, or during particular times of the year, to minimize the negative effects on wildlife.

Human society has created an ingenious system of transportation that allows coordinated and unfettered access to the Earth's land surface, but scientific research shows that there are multiple long-term ecological impacts of the growing global road network, most of which is in rural areas. To sustainably manage such a system, equally ingenious strategies need to be devised and implemented. Numerous approaches are already available for mitigating adverse ecological effects of rural roads, including best management practices, but barriers preventing their implementation exist including a lack of knowledge; a lack of will to implement unfamiliar or seemingly costly measures; a lack of care for the environment and future generations; and, in many regions, a lack of resources and capacity for governance. It is essential to educate citizens, drivers, and land managers alike about the true costs of roads, including their cumulative ecological impacts, and best management practices for mitigating their negative effects. Effectively translating this information into action could result in land use policy tools and management actions that are rooted in science, thus promoting a more holistic and sustainable approach to road development and management.

CASE STUDY 1

Elk Response to Recreational Activities on Rural Roads

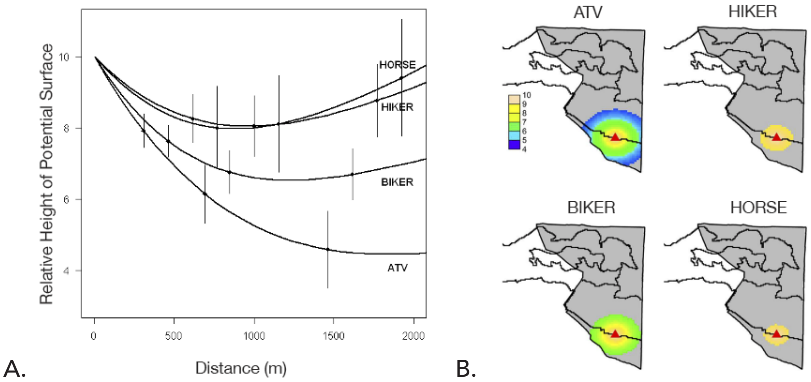

Figure 13. *Elk avoidance of four activities on rural roads: hiking (HIKER) and riding all terrain vehicles (ATV), bicycles (BIKER), and horses (HORSE). The slope of the curve (A) reflects strength of avoidance. Fine perpendicular lines show approximately 95-percent confidence bounds. Estimated potential surfaces (B) when human disturbance was located at the red triangle, showed by far the strongest avoidance was for ATV users, with the weakest for horseback riders. (Source: Preisler, H.K., A.A. Ager, M.J. Wisdom. 2013. Analyzing animal movement patterns using potential functions.* Ecosphere: *4[3]:art32.)*

Use of rural roads impacts wildlife when traffic and human presence cause disruptions, fragmenting habitats periodically. Using GPS technology, researchers in Oregon (USA) tracked Rocky Mountain elk *(Cervus canadensis nelsoni)* responses to recreational activities on rural roads. For four years, they tracked four kinds of recreational activities: hiking, riding bicycles, riding horses, and riding all-terrain vehicles (ATVs). They measured the reaction of elk by estimating a "potential surface", a statistical concept that describes the movement of animals as a space-time surface with points of attraction (e.g., foraging areas) and points of repulsion (e.g., disturbance caused by a vehicle). A mathematical equation was used to model the movement of the elk. That equation describes the strength of repulsion or avoidance as a function of distance to activity; the steeper the estimated function, the stronger the repulsion. The results showed that, on average, elk moved away when they were within a few hundred yards from any disturbances, but that "repulsion" was strongest for ATVs, with some repulsion observed up to 1 kilometer away. On the other hand, for horseback riders, the repulsion effect was only observed up to about 200m (Figure 13).

CASE STUDY 2

Gunnison Sage Grouse Responses to the Motorized use of Rural Roads

A growing number of studies collect information about seasonal, annual, and decadal changes in ecosystem responses to roads, providing information about animal movements and traffic patterns. Researchers in western Colorado conducted a study showing the effects of motor vehicles on rural roads on habitat use by Gunnison sage-grouse *(Centrocercus minimus).* The Gunnison sage-grouse (GUSG), a threatened species protected by the Endangered Species Act, is in decline with less than 5000 individuals remaining in the wild. Researchers established a vehicle monitoring network, collecting data on date and time of vehicle use as well as vehicle type, speed, and direction of travel, to study how the intensity of motorized use relate to GUSG habitat use and movements. The monitoring network has been in operation for six years, includes seven monitoring sites, and has counted more than 25,000 vehicles. The researchers also fitted 13 GUSG with GPS collars to monitor their habitat use and movements, or resource selection, in relation to motor vehicle use. Results of this project as they relate to motorized use of rural roads have shown a clear distinction between the effects of roads with "continuous" use and those roads with "infrequent" use. For continuous use roads (greater than two vehicles per day), GUSG resource selection increased within increasing distance from the road, up to over a kilometer away. This was compared with infrequently used roads (less than or equal to two vehicles per day) where resource selection occurred within ~200 m from roads. All roads, and their effects, are indeed not equal (Figure 14); throughout the year, GUSG will keep their distance from roads with relatively low but consistent traffic, as opposed to roads with extremely low and infrequent use. The effect of traffic is especially strong during late brood season, when birds are fully engaged in raising their young.

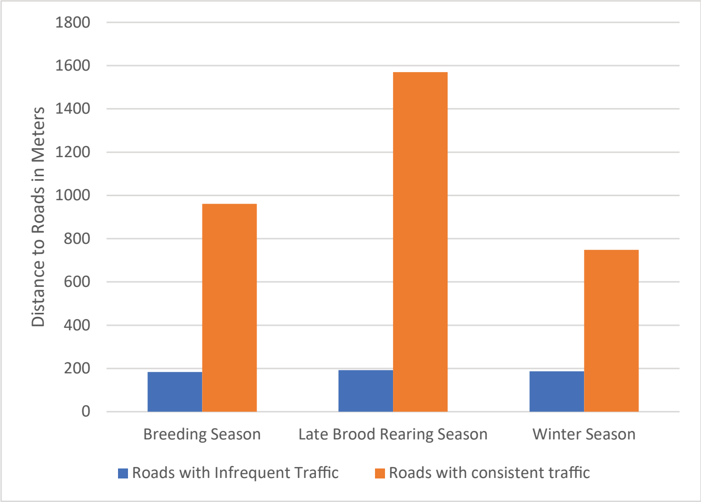

Figure 14. *Gunnison sage grouse seasonal distance to roads showing the effect of roads with consistent traffic and those with infrequent traffic.*

CASE STUDY 3

Vehicle Trails in the Doñana Natural Area, Spain

One of the areas in Europe with the lowest density of paved roads is the Doñana Natural Area in southwestern Spain (543 km²). Parts of it are open to the public, but access is severely restricted in the core area (Figure 15), suggesting that the Natural Area would be an excellent location as a roadless "control" for use in road ecology studies. Therefore, the public agency in charge of conservation (Consejería de Medio Ambiente, Junta de Andalucía) and a research institute (Estación Biológica de Doñana) conducted a research project to evaluate the role of unpaved roads and vehicle trails in the area. However, the agency found that the protected area holds more than 2000 km of vehicle trails occupying four percent of the surface area, with a density of 4 km km^{-2}. But, while access to the Doñana protected area is restricted, trail density is highest in the core area where it doubled from 1956 to 2010, and the lowest densities are in unprotected areas. Furthermore, traffic intensity is highest in the area with the most protection. This increased traffic intensity is due to higher levels of management, conservation, and research activities in the core area. Results from this work show that land management activities, in and of themselves, have impacts, often with consequences for the conservation of many species and communities, including several vegetation types considered high-priority habitats in the Doñana Natural Area.

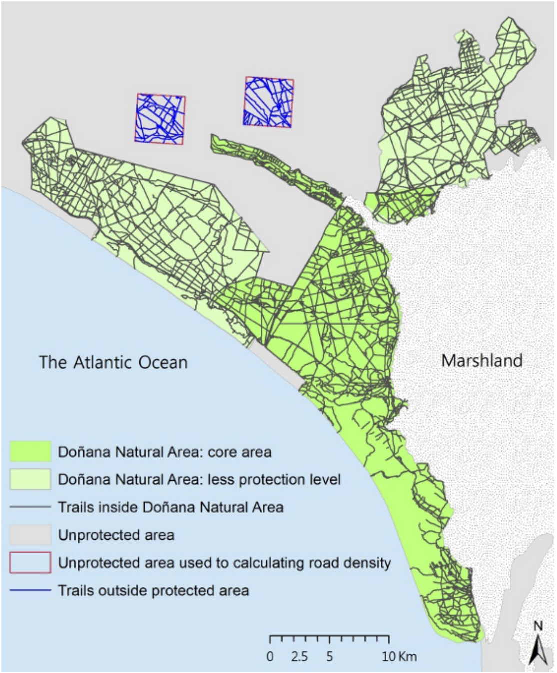

Figure 15. *Map of Doñana Natural Area, Spain. Core natural areas had just as many if not more trails within the protected area for scientific monitoring activities. (Source: Román J, A Barón, E Revilla. 2010. Evaluación de los efectos del tránsito a motor sobre especies y comunidades de interés en el Espacio Natural de Doñana. Consejería de Medio Ambiente, Junta deAndalucía y Estación Biológica de Doñana CSIC. 236 pp.)*

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FURTHER READING LIST

AASHTO Highway Subcommittee on Design Task Force for Environmental Design, editor. 1991. A Guide for Transportation Landscape and Environmental Design. American Association of State Highway and Transportation Officials, Washington, DC.

Balkenhol N., and L.P. Waits. 2009. Molecular road ecology: exploring the potential of genetics for investigating transportation impacts on wildlife. *Molecular Ecology* **18**(20): 4151-64.

Borda-de-Água L. , L. Navarro, C. Gavinhos, and H.M. Pereira. 2011. Spatio-temporal impacts of roads on the persistence of populations: analytic and numerical approaches. *Landscape Ecology* **26**: 253–265.

Borda-de-Água L., C. Grilo, and H.M. Pereira. 2014. Modeling the impact of road mortality on barn owl (Tyto alba) populations using age-structured models. *Ecological Modelling* **276**: 29–37.

Brundige, J. (Director). 2016. "Wild Ways." In *NOVA*, aired on April 20, 2016. Produced by WGBH, Boston, MA.

Ceia-Hasse A., L. Borda-de-Água, C. Grilo, and H.M. Pereira. 2017. Global exposure of carnivores to roads. *Global Ecology and Biogeography* **26**: 592-600.

Ellenberg, H., K. Müller, and T. Stottele, T. 1981. Straßen-Ökologie: Auswirkungen von Autobahnen und Straßen auf Ökosysteme deutscher Landschaften [Road ecology: Effects of motorways and roads on ecosystems in German landscapes.]. Ökologie und Straße: Broschürenreihe der deutschen Straßenliga [Ecology and road: Pamphlet series of the German Road League], Ausgabe [Issue] **3**: 19–122.

Fahrig, L., and T. Rytwinski. 2009. Effects of Roads on Animal Abundance: an Empirical Review and Synthesis. *Ecology and Society* **14** (1):21.

Faiz, A. 2012. The Promise of Rural Roads: Review of the Role of Low-Volume Roads in Rural Connectivity, Poverty Reduction, Crisis Management, and Livability. Transportation Resaerch Circular E-C167. Transportation Research Board of the National Academies, Washington, DC.

Forman, R.T.T., and L.E. Alexander. 1998. Roads and their major ecological effects. Annual Review of Ecology and Systematics **29**: 207–232.

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. Heanue, J.A. Jones, F.J. Swanson, T. Turrentine, and T.C. Winter. 2003. *Road ecology: Science and solutions*. Island Press, Washington, DC.

Haddad, N. M. 2015. Corridors for people, corridors for nature. *Science* **350**: 1166-1167.

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

IENE (Infra Eco Network Europe). 2015. Protect remaining roadless areas: The IENE 2014 declaration. *Nature Conservation* **11**: 1-4.

Keller, G., and J. Sherar. 2003. Low-volume roads engineering: Best management practices field guide. US Department of Agriculture, US Agency for International Development.

Kleinschroth, F., J. R. Healey, S. Gourlet-Fleury, F. Mortier, and R. S. Stoica. 2017. Effects of logging on roadless space in intact forest landscapes of the Congo Basin. *Conservation Biology* **31**:469-480.

Kuussaari, M., R. Bommarco, R.K. Heikkinen, A. Helm, J. Krauss, R. Lindborg, E. Öckinger, M. Pärtel, J. Pino, F. Rodà, C. Stefanescu, T. Teder, M. Zobel, and I. Steffan-Dewenter. 2009. Extinction debt: A challenge for biodiversity conservation. *Trends in Ecology and Evolution* **24**: 564–571.

Laurance, W.F.; M. Goosem, and S.G.W. Laurance. 2009. Impacts of roads and linear clearings on tropical forests. *Trends in Ecology and Evolution*, **24**, 659-669.

Laurance, W.F.; M.J. Campbell, M. Alamgir, M.I. Mahmoud. 2017. Road expansion and the fate of Africa's tropical forests. *Frontiers in Ecology and Evolution*, **5** (75).

National Research Council. 2005. Assessing and managing the ecological impacts of paved roads. The National Academies Press, Washington, DC.

Olson, D.D., J.A. Bissonette, P.C. Cramer, A.D. Green, S.T. Davis, P.J. Jackson, and D.C. Coster. 2014. Monitoring Wildlife-Vehicle Collisions in the Information Age: How Smartphones Can Improve Data Collection. *PLoS ONE* **9**(6): e98613.

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.

Rytwinski, T., K. Soanes, J.A.G. Jaeger, L. Fahrig, C.S. Findlay, J. Houlahan, R. van der Ree, E.A. van der Grift. 2016. How effective is road mitigation at reducing road-kill? A meta-analysis. *PLoS ONE* **11**(11): e0166941. doi: 10.1371/journal.pone.0166941. Online: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0166941.

Spanowicz, A.G., F.Z. Teixeira, F.Z., and J. A. G. Jaeger. 2020. An adaptive plan for prioritizing road sections for fencing to reduce animal mortality. *Conservation Biology*, 34(5):1210-1220. doi.org/10.1111/cobi.13502

Trombulak, S. C., and C. A. Frissell. 2000. Review of ecological effects of roads on terrestrial and aquatic communities. *Conservation Biology* **14**:18-30.

van der Grift, E. A., R. van der Ree, L. Fahrig, S. Findlay, J. Houlahan, J.A.G. Jaeger, N. Klar, L.F. Madrinan, and L. Olson. 2013. Evaluating the effectiveness of road mitigation measures. *Biodiversity and Conservation* **22**:425-448.

van der Ree, R., D.J. Smith, and C. Grilo. 2015. Handbook of Road Ecology. Wiley-Blackwell, Hoboken, NJ.

van Strien, M. J., K. W. Axhausen, I. Dubernet, A. Guisan, A. Grêt-Regamey, A. Khiali-Miab, D. O. Ortiz-Rodríguez, and R. Holderegger. 2018. Models of Coupled Settlement and Habitat Networks for Biodiversity Conservation: Conceptual Framework, Implementation and Potential Applications. *Frontiers in Ecology and Evolution* **6**:41.

BIBLIOGRAPHY

AASHTO. 2001a. Guidelines for Geometric Design of Very Low-Volume Local Roads (ADT less than or equal to 400). Washington, D.C.

AASHTO. 2001b. A Policy of Geometric Design of Highways and Streets. American Association of State Highway Transportation Officials, Washington, D.C.

AASHTO Highway Subcommittee on Design Task Force for Environmental Design, editor. 1991. A Guide for Transportation Landscape and Environmental Design. American Association of State Highway and Transportation Officials, Washington, DC.

Allan, J. D., and M. M. Castillo. 2007. Stream Ecology: Structure and function of running waters. 2 edition. Springer Netherlands.

Almeida-Neto, M., G. Machado, R. Pinto-da-Rocha, and A. A. Giaretta. 2006. Harvestman (Arachnida : Opiliones) species distribution along three Neotropical elevational gradients: an alternative rescue effect to explain Rapoport's rule? *Journal of Biogeography* **33**:361-375.

Angold, P. G. 1997. The impact of a road upon adjacent heathland vegetation: Effects on plant species composition. *Journal of Applied Ecology* **34**:409-417.

Balkenhol, N., and L. P. Waits. 2009. Molecular road ecology: exploring the potential of genetics for investigating transportation impacts on wildlife. *Molecular Ecology* **18**:4151-4164.

Ballesteros-Mejia, L., I. J. Kitching, W. Jetz, P. Nagel, and J. Beck. 2013. Mapping the biodiversity of tropical insects: species richness and inventory completeness of African sphingid moths. *Global Ecology and Biogeography* **22**:586-595.

Barbosa, N. P. U., G. W. Fernandes, M. A. A. Carneiro, and L. A. C. Junior. 2010. Distribution of non-native invasive species and soil properties in proximity to paved roads and unpaved roads in a quartzitic mountainous grassland of southeastern Brazil (rupestrian fields). *Biological Invasions* **12**:3745-3755.

Benten, A., P. Annighöfer, and T. Vor. 2018. Wildlife Warning Reflectors' Potential to Mitigate Wildlife-Vehicle Collisions—A Review on the Evaluation Methods. *Frontiers in Ecology and Evolution* **6**.

Bezborodov, G. A., D. K. Shadmanov, R. T. Mirhashimov, T. Yuldashev, A. S. Qureshi, A. D. Noble, and M. Qadir. 2010. Mulching and water quality effects on soil salinity and sodicity dynamics and cotton productivity in Central Asia. *Agriculture Ecosystems & Environment* **138**:95-102.

Blanton, P., and W. A. Marcus. 2009. Railroads, roads and lateral disconnection in the river landscapes of the continental United States. *Geomorphology* **112**:212-227.

Blomqvist, G., and E.-L. Johansson. 1999. Airborne spreading and deposition of de-icing salt — a case study. *Science of The Total Environment* **235**:161-168.

Borda-de-Água, L., C. Grilo, and H. M. Pereira. 2014. Modeling the impact of road mortality on barn owl (Tyto alba) populations using age-structured models. *Ecological Modelling* **276**:29-37.

Borda-de-Água, L., L. Navarro, C. Gavinhos, and H. M. Pereira. 2011. Spatio-temporal impacts of roads on the persistence of populations: analytic and numerical approaches. *Landscape Ecology* **26**:253-265.

Brown, G. P., B. L. Phillips, J. K. Webb, and R. Shine. 2006. Toad on the road: Use of roads as dispersal corridors by cane toads (Bufo marinus) at an invasion front in tropical Australia. *Biological Conservation* **133**:88-94.

Brunen, B., C. Daguet, and J. A. G. Jaeger. 2020. What attributes are relevant for drainage culverts to serve as efficient road crossing structures for mammals? *Journal of Environmental Management* **268**:110423.

Ceia-Hasse, A., L. Borda-de-Água, C. Grilo, and H. M. Pereira. 2017. Global exposure of carnivores to roads. *Global Ecology and Biogeography* **26**:592-600.

Coffin, A. W. 2007. From roadkill to road ecology: A review of the ecological effects of roads. *Journal of Transport Geography* **15**:396-406.

Coffin, A. W. 2010. Environmental Impacts of Roads. Encyclopedia of Geography. Sage Publications. Sage Publications, Thousand Oaks, USA.

Cornish, P. M. 2001. The effects of roading, harvesting and forest regeneration on streamwater turbidity levels in a moist eucalypt forest. *Forest Ecology and Management* **15**2:293-312.

Dark, S. J. 2004. The biogeography of invasive alien plants in California: an application of GIS and spatial regression analysis. *Diversity and Distributions* **10**:1-9.

Davidson, E. A., K. E. Savage, N. D. Bettez, R. M. Marino, and R. W. Howarth. 2010. Nitrogen in Runoff from Residential Roads in a Coastal Area. *Water Air and Soil Pollution* **210**:3-13.

Diseker, E. G., and J. M. Sheridan. 1971. Predicting Sediment Yield from Roadbanks. Transactions of the ASAE **14**:102-0105.

Dunlap, D. W. 1987. Development of grass-seeding specifications for use on Texas highway rights-of-way. Proceedings of Conference XVII International Erosion Control Association **18**:161-172.

Dunne, T., and L. B. Leopold. 1978. Water in Environmental Planning. W.H. Freeman and Company, New York.

Eisenberg, J. N. S., W. Cevallos, K. Ponce, K. Levy, S. J. Bates, J. C. Scott, A. Hubbard, N. Vieira, P. Endara, M. Espinel, G. Trueba, L. W. Riley, and J. Trostle. 2006. Environmental change and infectious disease: How new roads affect the transmission of diarrheal pathogens in rural Ecuador. Proceedings of the National Academy of Sciences **103**:19460-19465.

Ellenberg, H. K., K. Müller, and T. Stottele. 1981. Straßen-Ökologie: Auswirkungen von Autobahnen und Straßen auf Ökosysteme deutscher Landschaften [Road ecology: Effects of motorways and roads on ecosystems in German landscapes.]. Ökologie und Straße: Broschürenreihe der deutschen Strassenliga [Ecology and road: Pamphlet series of the German Road League] Ausgabe [Issue] **3**:19-122.

Fahrig, L., and T. Rytwinski. 2009. Effects of roads on animal abundance: an empirical review and synthesis. *Ecology and Society* **14** (1):21.

Faiz, A. 2012. The promise of rural roads: Review of the role of low-volume roads in rural connectivity, poverty reduction, crisis management, and livability. Transportation Research Circular.

Farmer, A. M. 1993. The effects of dust on vegetation: A review. *Environmental Pollution* **79**:63-75.

Fay, L., and X. Shi. 2012. Environmental Impacts of Chemicals for Snow and Ice Control: State of the Knowledge. *Water, Air, & Soil Pollution* **223**:2751-2770.

Forman, R. T. T. 1998. Road ecology: A solution for the giant embracing us. *Landscape Ecology* 13:III-V.

Forman, R. T. T., and L. E. Alexander. 1998. Roads and their major ecological effects. *Annual Review of Ecology and Systematics* **29**:207-232.

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. Heanue, J. A. Jones, F. J. Swanson, T. Turrentine, and T. C. Winter. 2003. *Road Ecology: Science and Solutions.* Island Press, Washington, DC.

Forsyth, A. R., K. A. Bubb, and M. E. Cox. 2006. Runoff, sediment loss and water quality from forest roads in a southeast Queensland coastal plain Pinus plantation. *Forest Ecology and Management* **221**:194-206.

Forys, E. A., C. Allen, and D. P. Wojcik. 2002. Influence of the proximity and amount of human development and roads on the occurrence of the red imported fire ant in the lower Florida Keys. *Biological Conservation* **108**:27-33.

Freudenberger, L., P. R. Hobson, S. Rupic, G. Pe'er, M. Schluck, J. Sauermann, S. Kreft, N. Selva, and P. L. Ibisch. 2013. Spatial road disturbance index (SPROADI) for conservation planning: a novel landscape index, demonstrated for the State of Brandenburg, Germany. *Landscape Ecology* **28**:1353-1369.

Haddad, N. M. 2015. Corridors for people, corridors for nature. *Science* **350**:1166-1167.

Haddad, N. M., L. A. Brudvig, J. Clobert, K. F. Davies, A. Gonzalez, R. D. Holt, T. E. Lovejoy, J. O. Sexton, M. P. Austin, C. D. Collins, W. M. Cook, E. I. Damschen, R. M. Ewers, B. L. Foster, C. N. Jenkins, A. J. King, W. F. Laurance, D. J. Levey, C. R. Margules, B. A. Melbourne, A. O. Nicholls, J. L. Orrock, D.-X. Song, and J. R. Townshend. 2015. Habitat fragmentation and its lasting impact on Earth's ecosystems. *Science Advances* **1**.

Hawbaker, T. J., and V. C. Radeloff. 2004. Roads and landscape pattern in northern Wisconsin based on a comparison of four road data sources. *Conservation Biology* **18**:1233-1244.

Hawbaker, T. J., V. C. Radeloff, M. K. Clayton, R. B. Hammer, and C. E. Gonzalez-Abraham. 2006. Road Development, Housing Growth, And Landscape Fragmentation In Northern Wisconsin: 1937–1999. *Ecological Applications* **16**:1222-1237.

Heffernan, J. B., P. A. Soranno, M. J. Angilletta Jr, L. B. Buckley, D. S. Gruner, T. H. Keitt, J. R. Kellner, J. S. Kominoski, A. V. Rocha, J. Xiao, T. K. Harms, S. J. Goring, L. E. Koenig, W. H. McDowell, H. Powell, A. D. Richardson, C. A. Stow, R. Vargas, and K. C. Weathers. 2014. Macrosystems ecology: understanding ecological patterns and processes at continental scales. *Frontiers in Ecology and the Environment* **12**:5-14.

Huling, E. E., and T. C. Hollocher. 1972. Groundwater Contamination by Road Salt: Steady-State Concentrations in East Central Massachusetts. *Science* **176**:288-290.

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

IENE, 2015. Protect remaining roadless areas: The IENE 2014 declaration. *Nature Conservation* **11**:1-4.

Jaeger, J. A. G. 2000. Landscape division, splitting index, and effective mesh size: new measures of landscape fragmentation. *Landscape Ecology* **15**:115-130.

Jaeger, J. A. G., R. Bertiller, C. Schwick, K. Müller, C. Steinmeier, K. C. Ewald, and J. Ghazoul. 2008. Implementing landscape fragmentation as an indicator in the Swiss monitoring system of sustainable development (Monet). *Journal of Environmental Management* **88**:737-751.

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

Joly, M., P. Bertrand, R. Y. Gbangou, M. C. White, J. Dube, and C. Lavoie. 2011. Paving the Way for Invasive Species: Road Type and the Spread of Common Ragweed (Ambrosia artemisiifolia). *Environmental Management* **48**:514-522.

Jones, J. A., F. J. Swanson, B. C. Wemple, and K. U. Snyder. 2000. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. *Conservation Biology* **14**:76-85.

Jordán-López, A., L. Martínez-Zavala, and N. Bellinfante. 2009. Impact of different parts of unpaved forest roads on runoff and sediment yield in a Mediterranean area. *Science of The Total Environment* **407**:937-944.

Jordán, A., and L. Martínez-Zavala. 2008. Soil loss and runoff rates on unpaved forest roads in southern Spain after simulated rainfall. *Forest Ecology and Management* **255**:913-919.

Jules, E. S., M. J. Kauffman, W. D. Ritts, and A. L. Carroll. 2002. Spread of an invasive pathogen over a variable landscape: A nonnative root rot on Port Orford cedar. *Ecology* **83**:3167-3181.

Karasin, B., Ibrahim, and E. Isik. 2016. Protection of Ten-Eyed Bridge in Diyarbakir. Budownictwo I *Architectura* **15**:87-94.

Keller, G., and J. Sherar. 2003. Low-Volume Roads Engineering: Best Management Practices Field Guide. Page 158. U.S. Department of Agriculture, U.S. Agency for International Development.

Kleinschroth, F., and J. R. Healey. 2017. Impacts of logging roads on tropical forests. *Biotropica* **49**:620-635.

Kleinschroth, F., J. R. Healey, S. Gourlet-Fleury, F. Mortier, and R. S. Stoica. 2017. Effects of logging on roadless space in intact forest landscapes of the Congo Basin. *Conservation Biology* **31**:469-480.

Kramer, M. G. 2013. Our Built and Natural Environments: A Technical Review of the Interactions Among Land Use, Transportation, and Environmental Quality.in E. P. Agency, editor. Government Printing Office, Washington, DC.

Kunert, N., L. M. T. Aparecido, N. Higuchi, J. d. Santos, and S. Trumbore. 2015. Higher tree transpiration due to road-associated edge effects in a tropical moist lowland forest. *Agricultural and Forest Meteorology* **213**:183-192.

Kuussaari, M., R. Bommarco, R. K. Heikkinen, A. Helm, J. Krauss, R. Lindborg, E. Öckinger, M. Pärtel, J. Pino, and F. Roda. 2009. Extinction debt: a challenge for biodiversity conservation. *Trends in Ecology & Evolution* **24**:564-571.

Laurance, W. F. 2013. Rapid Land-Use Change and its Impacts on Tropical Biodiversity. Pages 189-199 Ecosystems and Land Use Change. American Geophysical Union.

Laurance, W. F., M. J. Campbell, M. Alamgir, and M. I. Mahmoud. 2017. Road Expansion and the Fate of Africa's Tropical Forests. *Frontiers in Ecology and Evolution* **5**.

Laurance, W. F., G. R. Clements, S. Sloan, C. S. O/'Connell, N. D. Mueller, M. Goosem, O. Venter, D. P. Edwards, B. Phalan, A. Balmford, R. Van Der Ree, and I. B. Arrea. 2014. A global strategy for road building. *Nature* **513**:229-232.

Laurance, W. F., B. M. Croes, L. Tchignoumba, S. A. Lahm, A. Alonso, M. E. Lee, P. Campbell, and C. Ondzeano. 2006. Impacts of Roads and Hunting on Central African Rainforest Mammals. *Conservation Biology* **20**:1251-1261.

Laurance, W. F., M. Goosem, and S. G. W. Laurance. 2009. Impacts of roads and linear clearings on tropical forests. *Trends in Ecology & Evolution* **24**:659-669.

Lonsdale, W. M., and A. M. Lane. 1994. Tourist Vehicles as Vectors of Weed Seeds in Kakadu-National-Park, Northern Australia. *Biological Conservation* **69**:277-283.

Mathisen, K., A. Wójcicki, and Z. Borowski. 2018. Effects of forest roads on oak trees via cervid habitat use and browsing.

Mertens, B., R. Poccard-Chapuis, M. G. Piketty, A. E. Lacques, and A. Venturieri. 2002. Crossing spatial analyses and livestock economics to understand deforestation processes in the Brazilian Amazon: The case of Sao Felix do Xingu in South Para. *Agricultural Economics* **27**:269-294.

Mortensen, D. A., E. S. J. Rauschert, A. N. Nord, and B. P. Jones. 2009. The role of roads in plant invasions. *Invasive Plant Science and Management* **2**:191-199.

Moser, B., J. Jaeger, U. Tappeiner, E. Tasser, and B. Eiselt. 2007. Modification of the effective mesh size for measuring landscape fragmentation to solve the boundary problem. *Landscape Ecology* **22**:447-459.

National Research Council (U.S.). Committee on Ecological Impacts of Road Density. 2005. Assessing and managing the ecological impacts of paved roads. National Academies Press, Washington, D.C.

Nord, A. N., D. A. Mortensen, and E. S. J. Rauschert. 2010. Environmental Factors Influence Early Population Growth of Japanese Stiltgrass (Microstegium vimineum). *Invasive Plant Science and Management* **3**:17-25.

Olson, D. D., J. A. Bissonette, P. C. Cramer, A. D. Green, S. T. Davis, P. J. Jackson, and D. C. Coster. 2014. Monitoring Wildlife-Vehicle Collisions in the Information Age: How Smartphones Can Improve Data Collection. *PLOS ONE* 9:e98613.

Ouren, D. S., R. D. Watts, and A. W. Coffin. 2010. Beyond the pavement: Scientific methods for quantifying ecological responses to off-highway vehicle use. 95th ESA Annual Meeting, Pittsburgh, PA.

Pratt, C., and B. G. Lottermoser. 2007. Mobilisation of traffic-derived trace metals from road corridors into coastal stream and estuarine sediments, Cairns, northern Australia. *Environmental Geology* **52**:437-448.

Preisler, H. K., A. A. Ager, and M. J. Wisdom. 2013. Analyzing animal movement patterns using potential functions. *Ecosphere* **4**:art32.

Psaralexi, M. K., N.-E. P. Votsi, N. Selva, A. D. Mazaris, and J. D. Pantis. 2017. Importance of Roadless Areas for the European Conservation Network. *Frontiers in Ecology and Evolution* **5**:(2).

Ramakrishna, D. M., and T. Viraraghavan. 2005. Environmental Impact of Chemical Deicers – A Review. *Water, Air, and Soil Pollution* **166**:49-63.

Rauschert, E. S. J., D. A. Mortensen, O. N. Bjornstad, and A. N. Nord. 2008. The spread of Microstegium vimineum (Japanese stiltgrass), an invasive weed. 93rd Annual Meeting of the Ecological Society of America, Milwaukee, WI.

Rew, L., M. Taper, F. Pollnac, T. Brummer, and H. Balbach. 2010. Dispersal of plant propagules by vehicles.in Society for Range Management and Weed Science Society of America, Denver, Colorado.

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

Rytwinski, T., and L. Fahrig. 2013. Why are some animal populations unaffected or positively affected by roads? *Oecologia* **173**:1143-1156.

Rytwinski, T., K. Soanes, J. A. G. Jaeger, L. Fahrig, C. S. Findlay, J. Houlahan, R. van der Ree, and E. A. van der Grift. 2016. How Effective Is Road Mitigation at Reducing Road-Kill? A Meta-Analysis. *PLOS ONE* **11**:e0166941.

Rytwinski, T., R. van der Ree, G. M. Cunnington, L. Fahrig, C. S. Findlay, J. Houlahan, J. A. G. Jaeger, K. Soanes, and E. A. van der Grift. 2015. Experimental study designs to improve the evaluation of road mitigation measures for wildlife. J*ournal of Environmental Management* **154**:48-64.

Schuler, M. S., W. D. Hintz, D. K. Jones, L. A. Lind, B. M. Mattes, A. B. Stoler, K. A. Sudol, and R. A. Relyea. 2017. How common road salts and organic additives alter freshwater food webs: in search of safer alternatives. *Journal of Applied Ecology* **54**:1353-1361.

Selva, N., S. Kreft, V. Kati, M. Schluck, B.-G. Jonsson, B. Mihok, H. Okarma, and P. Ibisch. 2011. Roadless and Low-Traffic Areas as Conservation Targets in Europe. *Environmental Management* **48**:865-877.

Selva, N., A. Switalski, S. Kreft, and P. Ibisch. 2015. Why Keep Areas Road-Free? The Importance of Roadless Areas. Pages 16-26 in R. van der Ree, D. J. Smith, and C. Grilo, editors. Handbook of Road Ecology.

Siegert, N. W., D. G. McCullough, A. M. Liebhold, and F. W. Telewski. 2014. Dendrochronological reconstruction of the epicentre and early spread of emerald ash borer in North America. *Diversity and Distributions* **20**:847-858.

Siegert, N. W., R. J. Mercader, and D. G. McCullough. 2015. Spread and dispersal of emerald ash borer (Coleoptera: Buprestidae): estimating the spatial dynamics of a difficult-to-detect invasive forest pest. *The Canadian Entomologist* **147**:338-348.

Smith III, T. J., H. Hudson, M. B. Robblee, G. V. N. Powell, and P. J. Isdale. 1989. Freshwater Flow from the Everglades to Florida Bay: A Historical Reconstruction Based on Flourescent Banding in the Coral Solenastrea bournoni. *Bulletin of Marine Science* **44**:274-282.

Soanes, K., A. C. Taylor, P. Sunnucks, P. A. Vesk, S. Cesarini, and R. van der Ree. 2018. Evaluating the success of wildlife crossing structures using genetic approaches and an experimental design: Lessons from a gliding mammal. *Journal of Applied Ecology* **55**:129-138.

Sollenberger, L. E., K. R. Woodard, J. M. Vendramini, J. E. Erickson, K. A. Langeland, M. K. Mullenix, C. Na, M. S. Castillo, M. Gallo, C. D. Chase, and Y. López. 2014. Invasive Populations of Elephantgrass Differ in Morphological and Growth Characteristics from Clones Selected for Biomass Production. *BioEnergy Research* **7**:1382-1391.

Sosa-Pérez, G., and L. H. MacDonald. 2017. Reductions in road sediment production and road-stream connectivity from two decommissioning treatments. *Forest Ecology and Management* **398**:116-129.

Spanowicz, A. G., and J. A. G. Jaeger. 2019. Measuring landscape connectivity: On the importance of within-patch connectivity. *Landscape Ecology* **34**:2261-2278.

Stiles, J. H., and R. H. Jones. 1998. Distribution of the red imported fire ant, shape Solenopsis invicta, in road and powerline habitats. *Landscape Ecology* **13**:335-346.

Sullivan, J. J., P. A. Williams, S. M. Timmins, and M. C. Smale. 2009. Distribution and spread of environmental weeds along New Zealand roadsides. *New Zealand Journal of Ecology* **33**:190-204.

Sunnucks, P., and N. Balkenhol. 2015. Incorporating Landscape Genetics into Road Ecology. Pages 110-118 in R. van Der Ree, D. J. Smith, and C. Grilo, editors. Handbook of Road Ecology.

Tigas, L. A., D. H. Van Vuren, and R. M. Sauvajot. 2002. Behavioral responses of bobcats and coyotes to habitat fragmentation and corridors in an urban environment. *Biological Conservation* **108**:299-306.

Trombulak, S. C., and C. A. Frissell. 2000. Review of ecological effects of roads on terrestrial and aquatic communities. *Conservation Biology* **14**:18-30.

U.S. Department of Commerce, U.S. Census Bureau, Geography Division. 2014. TIGER/Line Shapefile, 2014, 2010 nation, U.S., 2010 Census Urban Area National.in U.S. Department of Commerce, U.S. Census Bureau, Geography Division, Editor, ftp://ftp2.census.gov/geo/tiger/TIGER2014/UAC/.

Urban, M. C., B. L. Phillips, D. K. Skelly, and R. Shine. 2008. A toad more traveled: The heterogeneous invasion dynamics of cane toads in Australia. *American Naturalist* **171**:E134-E148.

US EPA (US Environmental Protection Agency). 1993. Guidance Specifying Management Measures for Sources of Nonpoint Pollution in Coastal Waters., Washington, DC.

van der Grift, E. A., R. van der Ree, L. Fahrig, S. Findlay, J. Houlahan, J. A. G. Jaeger, N. Klar, L. F. Madrinan, and L. Olson. 2013. Evaluating the effectiveness of road mitigation measures. *Biodiversity and Conservation* **22**:425-448.

van der Ree, R., J. A. G. Jaeger, E. A. van der Grift, and A. P. Clevenger. 2011. Special Feature: Effects of Roads and Traffic on Wildlife Populations and Landscape Function. *Ecology and Society* 16(1):48.

van der Ree, R., D. J. Smith, and C. Grilo. 2015. Handbook of Road Ecology. John Wiley & Sons.

van Strien, M., K. Axhausen, I. Dubernet, A. Guisan, A. Grêt-Regamey, A. Khiali-Miab, D. Ortiz Rodriguez, and R. Holderegger. 2018. Models of Coupled Settlement and Habitat Networks for Biodiversity Conservation: Conceptual Framework, Implementation and Potential Applications.

Verburg, P., K. Kok, R. Pontius, and A. Veldkamp. 2008. Modeling Land-Use and Land-Cover Change.

Wang, G., X. Yan, F. Zhang, C. Zeng, and D. Gao. 2014. Traffic-Related Trace Element Accumulation in Roadside Soils and Wild Grasses in the Qinghai-Tibet Plateau, China. *International Journal of Environmental Research and Public Health* **11**:456.

Weiss, S. B. 1999. Cars, cows, and checkerspot butterflies: Nitrogen deposition and management of nutrient-poor grasslands for a threatened species. *Conservation Biology* **13**:1476-1486.

Werkenthin, M., B. Kluge, and G. Wessolek. 2014. Metals in European roadside soils and soil solution – A review. *Environmental Pollution* **189**:98-110.

Wisdom, M. J., A. A. Ager, H. K. Preisler, N. J. Cimon, and B. K. Johnson. 2004. Effects of off-road recreation on mule deer and elk. Transactions of the 69th North American Wildlife and Natural Resources Conference: 531-550.

Yan, X., D. Gao, F. Zhang, C. Zeng, W. Xiang, and M. Zhang. 2013. Relationships between Heavy Metal Concentrations in Roadside Topsoil and Distance to Road Edge Based on Field Observations in the Qinghai-Tibet Plateau, China. *International Journal of Environmental Research and Public Health* **10**:762.

Zehetner, F., U. Rosenfellner, A. Mentler, and M. H. Gerzabek. 2009. Distribution of Road Salt Residues, Heavy Metals and Polycyclic Aromatic Hydrocarbons across a Highway-Forest Interface. *Water Air and Soil Pollution* **198**:125-132.

Zhang, H., Z. Wang, Y. Zhang, M. Ding, and L. Li. 2015. Identification of traffic-related metals and the effects of different environments on their enrichment in roadside soils along the Qinghai–Tibet highway. *Science of The Total Environment* **521-522**:160-172.

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