Chapter 50
Charting the Path Ahead: Key Research Priorities in Road Ecology

Fernando Ascensão, Rafael Barrientos, Adam Ford, Airam Rodriguez, Alejandro Sánchez de Miguel, Alice C. Hughes, Andreas Kindel, Andrew F. Jakes, Anthony P. Clevenger, Benjamin B. Phillips, Benjamin Goldfarb, Brooke Maslo, Carlos Camacho, Carol Bannock, Cassie J. Thompson, Cecilia G. Leal, Charl Deacon,

F. Ascensão (✉)
Faculdade de Ciências Universidade de Lisboa, CE3C - Center for Ecology, Evolution and Environmental Changes & CHANGE – Global Change and Sustainability Institute, Lisbon, Portugal
e-mail: fjascensao@edu.ulisboa.pt

R. Barrientos
Road Ecology Lab, Department of Biodiversity, Ecology and Evolution, Faculty of Biology, Complutense University of Madrid, Madrid, Spain

A. Ford
Department of Biology, University of British Columbia, Kelowna, BC, Canada

A. Rodriguez
Departamento de Ecología Evolutiva, Museo Nacional de Ciencias Naturales (MNCN), Madrid, Spain

A. Sánchez de Miguel
Física de la Tierra y Astrofísica. Instituto de Física de Partículas y del Cosmos (IPARCOS), Universidad Complutense, Madrid, Spain

A. C. Hughes
School of Biological Sciences, University of Hong Kong, Hong Kong, Hong Kong

A. Kindel
Road and Railway Research Group, Ecology Post-Graduation Program, Federal University of Rio Grande do Sul, Porto Alegre, Brazil

A. F. Jakes
Wyoming Migration Initiative, Wyoming Cooperative Fish and Wildlife Research Unit, University of Wyoming, Laramie, WY, USA

A. P. Clevenger
Western Transportation Institute, Montana State University, Bozeman, MT, USA

B. B. Phillips
Environment and Sustainability Institute, University of Exeter, Exeter, UK

B. Goldfarb
Salida, CO, USA

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Christopher J. W. McClure, Clara Grilo, Clayton Lamb, Daniela Araya-Gamboa, Diego Varela, Edgar A. van der Grift, Federico Morelli, Fernanda Zimmermann Teixeira, Francisco Moreira, Fraser M. Shilling, Frederico Mestre, Guillermo Carmona,

B. Maslo
Department of Ecology, Evolution and Natural Resources, Rutgers, The State University of New Jersey, New Brunswick, NJ, USA

C. Camacho
Department of Ecology and Evolution - Doñana Biological Station CSIC, Seville, Spain

C. Bannock
NZ Transport Agency Waka Kotahi, Auckland, New Zealand

C. J. Thompson
Transport for NSW, Behavioural Ecology & Conservation Lab, The University of Sydney, Sydney, Australia

C. G. Leal
Lancaster Environment Centre, Lancaster University, Lancaster, UK

C. Deacon
Department of Conservation Ecology and Entomology, Faculty of Agrisciences, Stellenbosch University, Stellenbosch, South Africa

C. J. W. McClure
The Peregrine Fund, Boise, ID, USA

C. Grilo · F. Moreira
CIBIO, Centro de Investigação em Biodiversidade e Recursos Genéticos, InBIO Laboratório Associado/BIOPOLIS Program in Genomics, Biodiversity and Land Planning, CIBIO, Instituto Superior de Agronomia, Universidade de Lisboa, Vairão, Portugal

C. Lamb
Department of Biology, University of British Columbia, Kelowna, BC, Canada

D. Araya-Gamboa
Panthera-Costa Rica, San José, Costa Rica

D. Varela
Instituto de Biología Subtropical, CONICET- Universidad Nacional de Misiones, Argentina, Puerto Iguazú, Misiones, Argentina

E. A. van der Grift
Wageningen University & Research, Wageningen, The Netherlands

F. Morelli
Department of Life Sciences and Systems Biology, University of Turin, Turin, Italy

F. Zimmermann Teixeira
Center for Large Landscape Conservation, Bozeman, MT, USA

F. M. Shilling
Road Ecology Center, University of California, Davis, CA, USA

F. Mestre
CCMAR - Algarve Centre of Marine Sciences, Universidade do Algarve, Faro, Portugal

Hans M. Hanslin, Jacinto Román, James Baxter-Gilbert, Javier Hernandez-Hernandez, Javier Millán, Jayden E. Engert, Jesse N. Popp, Jochen A. G. Jaeger, Johannes Kollmann, Jones N. Darryl, Jorge E. Celi, Josie Stokes, Juan E. Malo, Keren Gila Raiter,

G. Carmona · J. Hernandez-Hernandez
Road Ecology Lab, Department of Biodiversity, Ecology and Evolution, Faculty of Biology, Complutense University of Madrid, Madrid, Spain

H. M. Hanslin
Norwegian Institute of Bioeconomy Research (NIBIO), Ås, Norway

J. Román
Department of Conservation Biology and Global Change - Doñana Biological Station CSIC, Seville, Spain

J. Baxter-Gilbert
Department of Biology, Mount Allison University, Sackville, NB, Canada

J. Millán
Instituto Agroalimentario de Aragón-IA2 (Universidad de Zaragoza-CITA) & Fundación ARAID, Zaragoza, Spain

J. E. Engert
Centre for Tropical Environmental and Sustainability Science, and College of Science and Engineering, James Cook University, Cairns, QLD, Australia

J. N. Popp
School of Environmental Sciences, University of Guelph, Guelph, ON, Canada

J. A. G. Jaeger
Department of Geography, Planning and Environment, Concordia University Montreal, Montréal, Québec, Canada

J. Kollmann
Chair of Restoration Ecology, TUM School of Life Sciences, Freising, Germany

J. N. Darryl
Griffith University, Brisbane, Australia

J. E. Celi
Water and Aquatic Resources Research Group, Ikiam Regional Amazon University, Tena, Napo, Ecuador

J. Stokes
City of Gold Coast Council, Gold Coast, Mail Centre QLD, Australia

J. E. Malo
Terrestrial Ecology Group (TEG-UAM), Department of Ecology and Centro de Investigación en Biodiversidad y Cambio Global (CIBC-UAM), Universidad Autónoma de Madrid, Madrid, Spain

K. G. Raiter
School of Biological Sciences, University of Western Australia, Perth, WA, Australia

K. Soanes
School of Agriculture, Forestry and Ecosystem Services, The University of Melbourne, Parkville, VIC, Australia

WSP Australia Pty Ltd, Melbourne, VIC, Australia

Kylie Soanes, L. Christine Paige, Laetitia M. Navarro, Larissa D. Biasotto, Mahmoud Ibrahim Mahmoud, Manisha Bhardwaj, Marcel P. Huijser, Margarita Mulero-Pázmány, Michael A. Weston, Michael J. Samways, Nuria Selva, Pablo Medrano-Vizcaíno,

L. C. Paige
Ravenworks Ecology, Hamilton, MT, USA

L. M. Navarro
Department of Conservation Biology and Global Change - Doñana Biological Station CSIC, Seville, Spain

L. D. Biasotto
BirdLife International, Cambridge, UK

M. I. Mahmoud
National Oil Spill Detection and Response Agency (NOSDRA), Abuja, FCT, Nigeria

M. Bhardwaj
Wildlife Ecology and Management, Faculty of Environment and Natural Resources, University of Freiburg, Freiburg, Germany

M. P. Huijser
Western Transportation Institute, Montana State University, Bozeman, MT, USA

M. Mulero-Pázmány
Department of Animal Biology. Facultad de Ciencias, University of Málaga, Málaga, Spain

M. A. Weston
Deakin Marine Research and Innovation Centre, School of Life and Environmental Sciences, Faculty of Science, Engineering and the Build Environment, Burwood, Australia

M. J. Samways
Department of Conservation Ecology and Entomology, Faculty of Agrisciences, Stellenbosch University, Stellenbosch, South Africa

N. Selva
Institute of Nature Conservation, Polish Academy of Sciences, Kraków, Poland

P. Medrano-Vizcaíno
Ecology and Evolutionary Biology, School of Biological Sciences, University of Reading, Reading, UK

P. Quiles
Road Ecology Lab, Department of Biodiversity, Ecology and Evolution, Faculty of Biology, Complutense University of Madrid, Madrid, Spain

P. F. Jones
Alberta Conservation Association, Lethbridge, AB, Canada

R. G. Seidler
Jackson Hole Wildlife Foundation, Jackson, WY, USA

R. T. Corlett
Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Menglun, Yunnan, China

Pablo Quiles, Paul F. Jones, Renee G. Seidler, Richard T. Corlett, Rodney van der Ree, Rodrigo Megía-Palma, Rui Lourenço, Sara M. Santos, Sarah Chiles, Sean P. Boyle, Silviu Petrovan,

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R. van der Ree
WSP Australia Pty Ltd, Melbourne, VIC, Australia

The University of Melbourne, Melbourne, VIC, Australia

R. Megía-Palma
Evolutionary Biology and Conservation Group. Department of Biodiversity, Ecology and Evolution, Faculty of Biology, Complutense University of Madrid, Madrid, Spain

R. Lourenço · S. M. Santos
MED—Mediterranean Institute for Agriculture, Environment and Development & CHANGE – Global Change and Sustainability Institute, UBC - Conservation Biology Lab, University of Évora, Évora, Portugal

S. Chiles
Living Lines, Nairobi, Kenya

S. P. Boyle
School of Science and the Environment, Grenfell Campus, Memorial University of Newfoundland and Labrador, Corner Brook, Newfoundland and Labrador, Canada

S. Petrovan
Conservation Science Group, Department of Zoology, University of Cambridge, Cambridge, UK

S. Santoro
Departamento de Ciencias Integradas, Facultad de Ciencias Experimentales, Universidad de Huelva, Huelva, Spain

S. R. Januchowski-Hartley
Florida International University, Miami, FL, USA

S. J. Milton
South African Environmental Observation Network, Arid Lands Node, Kimberley, South Africa

Wolwekraal Conservation and Research Organisation, Prince Albert, South Africa

S. B. Kroeger
Norwegian Institute of Bioeconomy Research (NIBIO), Ås, Norway

S. Haider
Institute of Ecology, School of Sustainability, Leuphana University of Lüneburg, Lüneburg, Germany

T. A. Schlacher
University of the Sunshine Coast, Maroochydore, Australia

T. A. Langen
Department of Biology, Clarkson University, Potsdam, NY, USA

T. Lennartsson
Swedish Biodiversity Centre at the Swedish University of Agricultural Sciences, Uppsala, Sweden

Simone Santoro, Stephanie R. Januchowski-Hartley, Suzanne J. Milton, Svenja B. Kroeger, Sylvia Haider, Thomas A. Schlacher, Tom A. Langen, Tommy Lennartsson, Trina Rytwinski, Victor J. Colino Rabanal, Wendy J. Collinson-Jonker, William F. Laurance, Yun Wang, and Marcello D'Amico

Abstract Road Ecology has experienced rapid growth as a field, yet significant knowledge and research gaps remain, particularly regarding underexplored impacts of roads on fauna and flora, ecosystems and landscapes, as mitigation methods and management solutions to avoid or reduce negative impacts. Here, we synthesize the key research needs identified throughout the book and emphasize topics that have received limited attention, highlighting the growing need for interdisciplinary and technologically advanced studies, and innovative statistical methodologies to assess infrastructure impacts and the combined effects of different types of infrastructures (such as roads and powerlines) on biodiversity. We highlight the need for more comprehensive studies on ecosystem functioning, evolutionary effects, and the role of roadside habitats, while calling for improvements in the cost-effectiveness of mitigation measures and large-scale assessments of road impacts. Emerging research priorities for Road Ecology include a growing emphasis on interdisciplinary and technologically advanced studies, and innovative statistical methodologies to assess infrastructure impacts and the combined effects of multiple infrastructures (such as roads and powerlines) on biodiversity. The impact of new infrastructure in areas

T. Rytwinski
Department of Biology, Carleton University, Ottawa, ON, Canada

V. J. Colino Rabanal
Department of Animal Biology, University of Salamanca, Salamanca, Spain

W. J. Collinson-Jonker
Centre for Functional Biodiversity, School of Life Sciences, University of KwaZulu-Natal, Pietermaritzburg, South Africa

W. F. Laurance
Centre for Tropical Environmental and Sustainability Science, and College of Science and Engineering, James Cook University, Cairns, QLD, Australia

Y. Wang
China Academy of Transportation Sciences, Beijing, China

M. D'Amico
Department of Conservation Biology and Global Change - Doñana Biological Station CSIC, Seville, Spain

supporting multiple migratory species is also becoming a priority issue, especially in regions where there is significant growth in infrastructure projects. Interdisciplinary efforts should prioritize strategies that balance infrastructure development with biodiversity conservation, especially in rapidly developing regions.

Keywords Global change · Horizon scanning · Knowledge gap · Research frontier · Road impacts · Study trends

50.1 Introduction

The field of Road Ecology is at a critical juncture, with a pressing need to deepen our understanding of both well-established and emerging impacts of transport infrastructure on fauna and flora, ecosystems and landscapes, and to integrate these lessons into project and infrastructure system planning to avoid or minimize negative impacts in the future. Despite being a relatively young field within ecology, Road Ecology has seen a significant increase in research in the last three decades. However, there are still marked regional variations across the globe (see section on Geographic Regions) and among focal organisms (see section on Organisms). Additionally, while certain topics such as the spatiotemporal patterns of road mortality (Chap. 1), the use of road passages and the mechanisms driving such use (Chaps. 33 and 34) have been extensively studied and are relatively well understood, several research areas remain largely underexplored or even entirely overlooked by the academic community.

Building on the insights gathered throughout the book, this final chapter identifies key research needs within the field of Road Ecology. It addresses both road impacts that have received limited attention and emerging topics that have either been overlooked or are just beginning to gain recognition in the field (Fig. 50.1). This chapter was collaboratively written, leveraging our collective expertise as scientists and practitioners in Road Ecology. Our goal is to present concise descriptions of research ideas and gaps that have sparked our interest; for detailed references, please refer to the respective chapters that inspired each topic. We emphasize that the topics highlighted here are not intended to be an exhaustive list. Instead, we aim to encourage the continued development of these and other areas, pushing the boundaries of Road Ecology and driving the research field forward. We hope that new research projects integrating expertise from diverse scientists will address these topics in the near future. This would allow movement toward a sustainable coexistence of human development and biodiversity.

Fig. 50.1 A metaphor for the broader scope of Road Ecology: infrastructure affects far more than charismatic, large-bodied species. Even small and often overlooked organisms (such as invertebrates during key reproductive periods, exemplified here by ground-dwelling beetles represented on a road sign in the Doñana Biological Reserve) can experience substantial disruption from roads and vehicle traffic. This highlights a central theme of the chapter: the need to move beyond a focus on roadkill and iconic fauna and adopt a more comprehensive, multispecies perspective on how transport infrastructure shapes ecological processes. (Photo by Jacinto Román)

50.2 Underexplored and Lesser-Known Impacts of Roads

50.2.1 Detecting "Invisible" Fragmentation

Habitat and landscape fragmentation is increasingly exacerbated by the presence of roads and rising traffic volumes, presenting a significant challenge to conservation efforts (Chap. 4). However, current research indicates that a large number of roads (both paved and unpaved ones), particularly in tropical regions, are not included in current maps and databases. This leads to an underestimation of the global fragmentation effects of roads. With road expansion expected to surge, especially in developing regions, there is an urgent need for accurate and up-to-date roadmaps to properly assess and avoid habitat loss and fragmentation. While current efforts to address fragmentation have primarily focused on restoring ecological corridors and constructing wildlife road crossings (Chaps. 33 and 34), the lack of knowledge about the effectiveness of these approaches across various organisms and the vast scale of road networks demands additional strategies. To keep pace with rapid development, innovative solutions such as automated mapping using artificial intelligence may become necessary (Chap. 42). Strategic road system planning, including the proactive designation of routes that minimize environmental impact and the identification of roads for removal, is crucial for reducing habitat loss and fragmentation (Chap. 4). However, the effectiveness of these approaches hinges on the availability and regular updating of comprehensive global roadmaps.

50.2.2 New Environmental Conditions Can Change Wildlife Interactions with Transportation Infrastructure

Road Ecology research has made substantial progress in understanding how roads influence wildlife movement, behavior, and spatial distribution (Chaps. 2 and 3). Such knowledge enables the prediction of wildlife crossing hotspots and the implementation of effective mitigation measures, such as fencing and crossing structures (e.g., over- or underpasses, canopy-bridges; Chaps. 33 and 34). These advances have also provided a more nuanced understanding of the role of light and noise pollution on wildlife movement and distributions, and evidence-based information for targeted mitigation strategies for a variety of situations. However, future changes in the landscape, such as increased traffic volumes, urban development, agricultural expansion and intensification, and climate-change effects, may further alter the spatiotemporal patterns of wildlife distribution and movement, and consequently, the locations where interactions with roads occur. This highlights the importance of incorporating potential land-use shifts into mitigation and conservation planning. For instance, for new road projects, we may need to install crossing structures that will only become necessary in future years. Conversely, if land-use policies are too lenient, the surrounding areas could be impacted and transformed, rendering crossing structures at these locations ineffective and turning them into dead-ends over time. We also need to identify areas where roads are likely to drive land-use changes, ensuring that we avoid placing mitigation efforts in regions destined to become highly urbanized or experience intensive agricultural development.

To obtain this level of proactive management, we need to understand how global change (land use and climate) will affect the movement and distribution of species, and for that we need long-term studies on animal movement, reproduction, and population demography. Scenario-based research is urgently needed to understand the effects of landscape changes on populations and therefore ensure that road design is future-proofed for biodiversity (Chaps. 24 and 26). The impacts of roads in developing economies also need more research, particularly pertinent in the context of biodiversity hotspots, where there is a high rate of human-induced environmental change coupled with significant risks related to biodiversity loss. These areas are likely to experience the most rapid and negative impacts in the coming years.

Rapid societal changes in the perception of the ecological crisis can reverse, modulate, or reinforce the success of biologically driven decisions like the delineation of wildlife corridors. Here, we can learn from positive case studies, such as the development of new roads in Costa Rica, where new infrastructure was paired with the designation of new protected areas to flank the road and prevent deforestation, so frequently associated with growing road networks (Chap. 24).

50.2.3 Effects of Light and Sound Pollution

The ecological impacts of road lighting and traffic noise are often overlooked in research, despite their critical importance (see Chaps. 5 and 6). These sources of sensory pollution can adversely affect a wide range of taxa, yet the cascading effects on populations, communities, and ecosystems remain poorly understood. Similarly, the interactions between illumination and noise, as well as their combined effects with other disturbances like chemical pollution (Chap. 7) or dust loads, are not well-documented. The impacts of road lighting and noise are particularly detrimental where roads cross high-value natural and wilderness areas, especially for guilds of photophobic nocturnal species for which road and traffic lighting may pose a barrier even on quieter, less-used new roads. This includes whole guilds of photophobic nocturnal species for which road and traffic lighting may pose a barrier even on quieter, less used new roads. Conversely, we need to understand the impacts of potentially rapid upcoming changes in road technologies, for example, massive adoption of electric vehicles and autonomous vehicles, and changes toward LED road lighting, which may dramatically reduce or alter certain light and sound pollutants, while potentially increasing others, with unknown consequences. Another common and yet understudied impact of traffic is vibration pollution, across the air and soil, on biodiversity. The interface of ecoacoustics, vibroscape (substrate-borne vibrations), biotremology (study of production, dispersion, and reception of mechanical vibrations by organisms, and their effect on behavior), and other related concepts and Road Ecology is still in its infancy.

50.2.4 Effects of Physiological Stress on Wildlife

Physiological stress caused by roads is often overlooked (Chap. 9). Integrating stress physiology studies into Road Ecology can be achieved by measuring biomarkers of stress, such as glucocorticoids, from various biological materials, such as plasma, excretions, and keratinized tissues. Plasma samples provide insights into short-term stress responses, while materials like keratinized tissues reflect longer-term stress effects. Understanding these stress responses can help to infer how animals cope with chronic or acute disturbances caused by roads, a crucial step toward attempting effective mitigation. Future studies in Road Ecology should prioritize basic knowledge across diverse taxa and link glucocorticoid changes to fitness outcomes and their community- and ecosystem-scale effects. Collaborations with specialized laboratories are essential for accurately measuring hormone levels, thereby enhancing our ability to assess and mitigate the ecological impacts of roads on wildlife.

Glucocorticoids are not the only metric for measuring physiological stress, however, and there remains a wide variety of underutilized biomarkers related to the activation and function of the hypothalamic–pituitary–adrenal axis, the autonomic nervous system, and the immune system that could be applied to road-related stress physiology studies in the future.

50.2.5 Beyond Impacts on Wildlife: Effects on Populations and Ecosystem Functioning

Understanding the impacts of roads on ecosystem functioning, rather than focusing solely on wildlife individuals and single species, is crucial for effective conservation (Chap. 12; Fig. 50.1). Only recording roadkill does not inherently reflect population-level impacts or the intensity of those impacts. Roadkill and other road-related effects can have far-reaching impacts on regional ecological communities by weakening or even severing wildlife and nonwildlife interactions, following changes in population abundance or local extinctions, as roads do not affect all species equally (Chap. 14). Similar effects are known for defaunated tropical rainforests. The resulting simplification of ecological network structures, such as food webs, can alter the flow of matter and energy, and thus affect ecosystem functioning, and ultimately disrupt the provision of ecosystem services. This simplification of trophic chains can also lead to indirect shifts in species distributions, for instance, such as roadkill reduces prey density or alleviates predator pressure. Understanding the fundamental effects of road-induced wildlife mortality and behavioral changes on ecological networks is essential for managing the impacts of human activity on biodiversity; however, they remain largely unexplored.

Empirical Road Ecology studies are often conducted at local scales; however, there is a pressing need for regional and macroecological approaches to understand the broader-scale and/or community-level effects of road networks on community stability, resistance, resilience, and ecosystem services (Chaps. 15, and 16). This includes analyzing spatial and temporal patterns of mortality, abundance, reproduction, dispersal rates, and species interactions across the whole fabric of ecosystems. However, obtaining and integrating this information across multiple species and scales is one of the most challenging aspects of Road Ecology. To facilitate large-scale studies, it is essential to establish and adopt standardized data collection and sharing protocols and curate existing datasets, enabling comprehensive spatial approaches. Genetic approaches can provide valuable insights into population gene flow, dynamics, and viability (Chap. 38), which can be integrated with remote sensing data (Chap. 42) and other key information to better understand changes in ecosystem functioning.

50.2.6 Can Roads Trigger Evolutionary Effects?

The impacts of roads on plant and animal evolution are beginning to be understood through relative fitness comparisons between road-affected and unaffected populations (see Chap. 13). Studies on species that have documented phenotypic changes due to road effects provide valuable insights, especially when samples are available from before and after road construction. Techniques such as reciprocal transplant and common garden experiments, along with multigenerational studies and crossbreeding designs, can help distinguish between genetic and plastic effects of road impacts on functional traits. Estimating or reconstructing individual dispersal events from movement-tracking data and molecular markers may help understand the contribution of roads to genetic isolation of populations. High-throughput sequencing techniques also offer promising opportunities for future research into the evolutionary implications of roads on populations and species.

50.2.7 Roadside Habitats

There is now substantial evidence that roadside verges can serve as habitat for various species, offering important refuges for different plants and animals, particularly in more degraded landscapes, and including both native and non-native species (Chap. 17 and 19). For example, in Australia, particularly in areas outside urban centers, the roadside environment is sometimes the only wildlife refuge as these areas have been largely cleared for agriculture. Roadside reserves can also be important areas for threatened species refuge and for wildlife movement between patches of remnant vegetation. In many European landscapes, road verges are important refuges for species that have formerly been widespread in agricultural landscapes, but which are now declining due to, for example, abandonment of semi-natural pastures.

There is a need to establish a well-developed theoretical framework of roadside habitats that integrates environmental conditions, ecological processes (including human management), and landscape influences. A deeper understanding of the ecosystem services provided by road verges, such as biodiversity conservation, carbon sequestration, and pollination (see Chap. 20), is essential for this theoretical development. Additionally, we need to understand how verge habitat and human management may affect the persistence of different species in these habitats. In contrast, while it is commonly accepted that roadside habitats favor the establishment of non-native plant species, far less is known about the spread of (introduced) pathogens and other microorganisms along roads.

There is still limited understanding of whether the benefits of roads as refuge are outweighed by the risks of ecological traps—when attractive habitats become demographic sinks due to locally reduced reproduction or increased mortality (Chap. 8). Thus, it is important to assess for which species, and under what circumstances, road verges may function as alternative habitat areas where populations can thrive or, conversely, become ecological traps. Ultimately, it is crucial to determine whether road planning, design, and construction can maximize the habitat value and ecosystem services of road verges while minimizing the likelihood of these areas becoming ecological traps. Constructing roadside habitats that support populations of species, thereby contributing to biodiversity conservation, may be seen as one additional way to mitigate negative effects of the transportation system. Conversely, it will be critical to determine under which circumstances "improved roadside verges" might in fact become "mitigation traps" for a suite of different species, giving the appearance of an ecological value added from road systems, but resulting in a net loss of values, especially when compared to non-roadside areas.

50.2.8 Eco-hydrological Impacts and Their Solutions

The eco-hydrological impacts of transport infrastructure are vast and often overlooked, but can pose serious threats to ecosystems by altering water availability and flows, increasing erosion, and destabilizing landscapes (Chap. 18). Although they affect the very fundamentals of ecosystems—water, soil, and nutrients—research on identifying and addressing these impacts remains limited. Studies are urgently needed to better predict where and how eco-hydrological impacts will manifest in new developments and how they can be avoided or mitigated—what ecosystems and landscapes will become water-starved if overland sheetflow is disrupted and which water redistribution structures are the most effective in re-establishing sheetflows? Which fish and other aquatic species are at risk of habitat fragmentation caused by unpassable road crossings due to high water velocities, inadequate flow depth, and the like? Can improved culvert hydraulics and fish ladders at road crossings mitigate such impacts? How can roads be designed to better avoid or reduce the surface water magnification effect and drastic changes to the geomorphology, water redistribution, and soil and nutrient resources in the surrounding catchments?

Research is needed to develop hydrologically considerate road design solutions such as permeable materials, properly designed culverts, and energy dissipation zones to prevent stream diversion, impedance and gully erosion, severely compromising stream function and stability. Improvements in environmental monitoring, such as real-time sensors of water quality (including pollution and sedimentation), turbulence and velocity, as well as soil moisture and salinity can provide researchers with better insights into impacts and solutions. Similarly, techniques for remote sensing of soil moisture, vegetation photosynthetic activity, and elevation offer promising opportunities for providing early warnings of impacts and predicting and studying eco-hydrological impacts at larger scales and developing effective solutions. Ultimately advanced hydrological catchment models that simulate the complex interactions between road networks and watershed dynamics should be integrated with models of other road-related ecological impact pathways to guide proactive mitigation efforts in changing climates. Alongside these, further research into the benefits and best use of ecological engineering solutions like bioswales and wetland restoration along roadways to manage water flow, capture pollutants and sediment, and restore natural processes is needed.

50.3 Emerging Topics in Road Ecology

50.3.1 Improving the Cost-Effectiveness of Roadkill Mitigation

Over the past three decades, significant efforts have been made to mitigate the impact of roads on wildlife, particularly those related to wildlife–vehicle collisions, with exclusion fences proving to be more effective in preventing roadkills than other measures, such as animal detection systems or wildlife reflectors (see Chaps. 33 and 34). However, the effectiveness of these measures is often not evaluated from an individual-level or population-level perspective but rather in terms of building safe roads at minimal cost. It is crucial to properly address the cost-effectiveness of roadkill mitigation measures to ensure efficient resource allocation and maintain public support. In particular, future research should focus on understanding how fence-following distances influence the fence-end effect and on predicting fence effectiveness based on fence length for different species. Given that fence-following behavior varies across species, especially among migratory animals, more studies are needed to quantify these distances and categorize animal–fence interactions. Researchers should also incorporate these movement patterns into individual-based models and validate them through field studies conducted before and after fence construction.

Accurate economic evaluations require a comprehensive accounting of the costs and financial benefits of mitigation measures, including all costs associated with wildlife–vehicle collisions (see Chap. 35). The distribution of costs among stakeholders must also be considered, as the cost-effectiveness of a measure can vary depending on who bears the costs and who reaps the benefits. Standardized frameworks for reporting costs are essential for ensuring data comparability across studies, but ultimately this will only work if information about such costs is shared and made available, which is currently not the case. Anonymized sensitive cost data reporting and an emphasis on the inclusion of such data when reporting road mitigation might prove important steps forward. Prioritizing the evaluation of which measures provide the best outcomes for a given cost should be a key focus, necessitating more real-world studies that calculate the costs and cost-effectiveness of various mitigation strategies. Additionally, synthesizing data on effectiveness and costs into online databases would serve as valuable decision-making resources for the ecological mitigation community.

50.3.2 Large-Scale Transportation System Assessments

Large-scale assessments of the impacts of transportation infrastructure on wildlife populations and ecosystems are essential as road construction continues to expand globally (see Chap. 36). Key principles for such assessments include time-series analysis, which involves monitoring landscapes and road effects over time to establish thresholds for ecosystem functioning, including wildlife population persistence (see Chap. 12). To support robust large-scale assessments, it is critical to improve the quality and quantity of regional-scale surveys (e.g., data collection standardization and sharing). These studies should encompass a variety of landscapes, ecosystem contexts, road types, and traffic volumes. Spatially explicit analyses and multi-species approaches provide more reliable data on the impacts of roads on animal and plant populations and communities. Accurate large-scale assessments are vital for establishing baseline information to understand broad-scale patterns of road effects and to inform strategies that make road networks less detrimental to biodiversity and more sustainable.

This approach may become more important in developing and middle-income countries. The rapid expansion of global infrastructure, particularly in biodiverse regions, presents a significant challenge to biodiversity conservation. Major infrastructure development programs are now on track, the most ambitious being China's Belt and Road Initiative (see Chap. 44). A major challenge for Road Ecology is to influence public policy and decision-makers toward a more sustainable road network development and to further mainstream Road Ecology into development and conservation policies. Moving forward, improving our knowledge of the intricate interplay between conservation policies, Road Ecology, and socioeconomic development will be essential for more sustainable decision-making and the development of effective policies across sectors of the economy and society (see Chap. 49). Moreover, the same processes act for several other infrastructure networks, and knowledge attained from Road Ecology can boost the improvement of environmentally driven decisions done in other sectors.

50.3.3 Roadless Areas

Roadless areas are increasingly rare. These regions can be vital refuges for wildlife, offering a shield from industrial extraction, agriculture, urbanization, tourism, water development, and other human activities that cause ecological harm. While the identification of all the remaining roadless areas is challenging due to the incompleteness of road mapping, identifying, protecting and restoring the roadless areas is a crucial and yet underutilized approach within Road Ecology (Chap. 37). This practice must become a key growth area for the field to ensure the survival and flourishing of many ecosystems. However, significant questions remain, namely on the optimal size for these "roadless areas," and understanding how much biodiversity and ecological functions might be lost if smaller areas were implemented. The appropriate scale should guide decisions about whether to enhance or upgrade alternative routes, a topic closely linked to the SLOSS (Single Large or Several Small) debate in conservation biology. This issue is also tied to the extent of habitat disturbance and degradation around road networks, as well as the demographic effects on rare species that have low population densities and require large territories. Addressing these complexities is essential for developing effective strategies to protect and sustain these critical ecological zones.

50.3.4 Functional Understanding Through Trait-Based Models

Species traits, including morphology, behavior, ecology, and physiology, play a crucial role in determining a species' intrinsic vulnerability to road impacts. However, few studies have thoroughly examined species traits to understand these impacts (see Chap. 39). Limitations such as the availability and biases of trait data often hinder their use in research. To support future work, it is essential to compile field trait data carefully and make databases publicly accessible. Vulnerability assessments to road impacts can be conducted using fitted trait-based models or by defining vulnerability criteria based on intrinsic and extrinsic factors. Direct predictions from fitted models are generally applicable only to closely related, unstudied species, whereas defining risk categories based on vulnerability criteria allows for more generalized assessments (see Chap. 39). These criteria may include species' predicted risk from trait-based models or cumulative risks from various road impacts. Conversely, for species using verges as habitats, criteria should aim at connecting species' ecological requirements to the potential habitats a road verge can offer. Importantly, any vulnerability assessment must consider the implications for long-term population persistence. Defining the best approach for translating trait-based model results into vulnerability criteria and developing a global protocol for assessing road impacts requires transparent and best-practice consultation (e.g., via a Delphi technique) among stakeholders in the field of Road Ecology.

50.3.5 Engaging the Diverse Public in Road Ecology Research

Road Ecologists come from diverse cultural and racial backgrounds, and the field must stay inclusive of underrepresented diverse communities in science, policy, and practice. It is essential to continue striving for greater inclusivity across all aspects, including science, policy, and practice. The integration of volunteer data collection (also known as citizen science or community-based science) into transportation-related environmental studies offers a valuable opportunity to enhance knowledge and build community capacity (see Chap. 41). However, it requires a deep understanding of the diverse group of volunteers involved. Tools and studies must be designed to accommodate the varying goals, motivations, and capabilities of these volunteers.

While volunteer data collection has traditionally focused on established programs like air quality monitoring, there is now a significant potential for broader involvement in Road Ecology research. The use of handheld devices and apps has become increasingly prominent in volunteer data collection, such as recording roadkill observations. In addition, other data types obtained from community science can be highly valuable for Road Ecology, namely information on species presence in the vicinity of roads (e.g., from eBird, iNaturalist), and information on movement behavior, namely near roads, for example, from videos from online platforms. Nevertheless, the effectiveness and inclusivity of community science data require thoughtful evaluation.

To ensure meaningful outcomes for decision-making, analyses of volunteer-collected data must carefully consider sampling approaches, potential biases, and data quality. Implementing a blockchain approach could address concerns about data reliability, enabling transparent metadata tracking throughout the data collection process (Chap. 41). While this approach presents challenges, it has the potential to significantly improve data quality and utilization in transportation decision support, provided there is agreement on standards and sufficient funding for the development and dissemination of these tools.

50.3.6 Technological and Analytical Advancements

Technological advancements in animal-borne devices, remote-triggered cameras, bioacoustic sensors, unmanned aircraft systems, or new molecular approaches hold significant promise for enhancing data collection and analyses in Road Ecology, especially when paired with AI or deep learning to automate species identifications. These innovations include improvements in device autonomy, data storage capacity, and connectivity through wireless communications, enabling real-time data transmission, namely for gathering roadkill data from high-speed railways and highways. Drones offer a cost-effective method for gathering high-resolution aerial images, which can be used to assess the effects of roads on surrounding vegetation, hydrological changes, and animal distribution. Additionally, advancements in artificial intelligence, such as machine learning, facilitate ecological studies by enabling the classification of species in camera-trap images and bioacoustic recordings. Wireless sensor networks and Internet-of-Things technologies further contribute to ecological research by allowing for high-frequency data sampling and shared use of wireless infrastructure, supporting reliable and cost-efficient data collection. These technologies also extend to traffic management, where they help reduce roadkills by alerting drivers to the proximity of animals and providing traffic flow information. There is a vast amount of information being collected by a multitude of sensors that could be used in research, such as traffic cameras, weather radars, self-driving vehicles, etc. All this information could be integrated into pipelines of data processing that could feed ecological models and assessment of road-related impacts, for example, likelihood of animal collisions with vehicles (see Chap. 42).

Importantly, however, the widespread use of data collection devices raises ethical concerns regarding data privacy and social implications, making it necessary to establish guidelines and protocols for the responsible use of technology in Road Ecology. In this evolving landscape, it is essential to acknowledge that analyzing ecological patterns is challenging due to the hierarchical nature of data. For example, an animal on the road may be killed, but its carcass may not remain visible during surveys, and observers may not detect it. Neglecting these processes may risk overlooking the true drivers of spatiotemporal observation patterns and can lead to incorrect conclusions about the impact of roads and traffic. Therefore, integrating advanced analytical methodologies with technological innovations is crucial for accurately assessing road impacts and understanding how roads affect ecosystems (Chap. 40).

50.3.7 Off-Road Driving and Its Impacts

Off-road vehicles provide access to many otherwise-inaccessible areas, increasing the risk of poaching, resource discovery and exploitation, wildlife disturbance, ignition of wildfires, spread of disease and invasive species, and other negative impacts. Engineering advancements in off-road vehicles have traditionally focused on safety, efficiency, ergonomics, and terrain-handling capabilities, often overlooking their direct ecological impacts (see Chap. 43). However, recent developments, such as improved terramechanics and automation, offer potential to mitigate these impacts by reducing erosion, landscape scarring, and wildlife collision rates. The shift to electric powertrains in off-road vehicles may further influence ecological outcomes, potentially lowering noise disturbance for wildlife but also introducing new challenges, such as the possibility of increased collision rates. Regulations, enforcement, and driver behavior play critical roles in shaping the ecological impact of off-road vehicles, yet the scientific understanding of these interactions remains limited. The growing popularity of recreational off-road vehicle use presents significant challenges for biodiversity conservation, particularly in protected areas. To address these challenges, understanding the effectiveness of the implementation of comprehensive regulatory frameworks and the promotion of responsible driver behavior toward reducing the ecological impacts of off-road vehicles are essential steps.

Related to off-road traffic, the effects of unpaved roads and walking and cycling trails have seldom been addressed. Unpaved roads are probably the largest road system in the world, traversing millions of hectares of rangelands in arid and semi-arid areas as well as in tundras, forests, and alpine environments. Many are poorly maintained or abandoned following discontinued mining, logging, or military operations. The economic and ecological cost of active and abandoned unpaved roads via soil erosion, lateral gully formation, and facilitation of invasive alien plants has rarely been quantified. In addition, these roads provide paths for people to access otherwise remote areas, increasing the occurrence of road-related human impacts.

50.3.8 Long- and Short-Distance Effects on Below-Ground Diversity

In comparison with other taxonomic and functional groups, we still know relatively little about soil biodiversity in general. This global data gap impairs the assessment of the below-ground impacts of roads and other linear infrastructure. Such assessment must go beyond species diversity and richness, or community composition, and also include measures of effects on below-ground ecosystem structure and functioning, and indirectly on ecosystem services supply. Importantly, measuring the effects of roads on soil diversity also requires considering long-distance impacts and telecoupling along the different steps of the road production chain, that is, raw material extraction and transport to the site where the infrastructure is being built.

50.3.9 Combined and Cumulative Effects of Roads and Other Linear Infrastructures

The combined impacts of roads, railways, powerlines (and other energy-related structures), and fences on wildlife and ecosystems are critically understudied, particularly regarding their cumulative and synergistic effects (see Chaps. 45–47). Fences, like other forms of linear infrastructure, pose significant challenges to wildlife movement and ecological connectivity, often exacerbating the barrier effects already caused by roads and railways (see Chap. 45). Research is urgently needed to assess how these infrastructures collectively impact species, populations, communities, and ecosystem functions. For example, aligning powerlines with existing roads is often recommended to reduce disturbance, but there is little scientific evidence supporting this approach, and it may worsen barriers to wildlife movement. Similarly, fences should be made more permeable or removed entirely in areas where they are not needed, to reduce their ecological impact. In locations where fencing is essential, it is crucial to incorporate wildlife corridors that allow animals to bypass fences along their migration routes. Of particular concern, yet often understudied, are the effects of border fences in transboundary regions (areas near or adjacent to international political boundaries), which can obstruct species from accessing critical parts of their range across countries.

Comparative studies on roads vs. railways, fences or powerlines, and their respective ecological impacts are also lacking, with fences and railways being particularly understudied (see Chaps. 46 and 47). With fences, research is even more problematic, given the lack of data. Mapping fences from remote imagery is difficult, whereas physically mapping them on the ground is time consuming. As such, fences remain mostly unavailable for evaluating their effects on wildlife and ecosystem processes to resource managers. In addition, it is even more difficult to differentiate fence attributes (e.g., is a fence a four-strand barbed wire fence or is it a woven wire fence).

50.4 Concluding Remarks

As we advance through the UN's declared "Decade on Ecosystem Restoration," it is crucial to recognize that roads (along with other linear infrastructure) represent some of the most disruptive human interventions in ecosystems. These structures should be primary targets for restoration and mitigation efforts. Road Ecology has a pivotal role to play in these initiatives by offering insights, analyses, and strategies developed within the field. However, addressing the ecological impacts of roads must go beyond purely environmental considerations. In many developing countries, the demand for linear transportation infrastructure is driven by the need to meet essential life requirements, which often creates a conflict between development and ecological conservation. Therefore, solutions must be holistic, integrating economic, social, ecological, and other relevant dimensions. Only through comprehensive research can effective policies be developed to support local governments in making informed decisions.

Throughout this book, we have explored a wide range of topics related to the various impacts of roads, addressing the unique characteristics of different geographic regions, focusing on diverse organisms, and highlighting emerging issues within this field. However, as we conclude, this chapter illustrates that despite significant progress in Road Ecology, many areas remain notably underexplored. Addressing these knowledge gaps is essential for enhancing the evaluation of infrastructure projects, promoting more sustainable road planning that accounts for both human and ecological needs, and developing resilient landscapes that benefit both wildlife and people (Fig. 50.1). We emphasize that the topics discussed here are not exhaustive and highlight the need for further exploration.

A recurring theme across all chapters is the lack of systematic approaches to knowledge in terms of rating systems or other performance-based frameworks, including their associated regulations, incentives, commitments, controls, penalties, and rewards. These systems are crucial for evaluating and monitoring the adoption of the best practices outlined throughout this book. Although performance systems in the transport sector have been in development for some time, they often lack adequate focus on biodiversity, highlighting an urgent need for improvement. The pursuit of more sustainable transport systems is closely tied to various Sustainable

Development Goals (SDGs), with ongoing formal planning processes aimed at advancing these goals within the transport sector in the coming decades. In addition to enhancing the integration of biodiversity-related indicators, it is also critical to assess the level of adoption of rating systems or other biodiversity performance tools across SDG signatory countries. Understanding the effectiveness of these instruments in driving positive on-the-ground outcomes for mitigating the diverse impacts of roads on biodiversity is a key step toward realizing sustainable infrastructure solutions.

Given the rapid expansion of road networks, particularly in the Global South, it is essential to form multidisciplinary consortia that bring together diverse scientific expertise. Such collaborative efforts will provide a comprehensive understanding of Road Ecology, leading to integrated solutions that balance human development with conservation goals. Road Ecology should also leverage the extensive experience of other disciplines in integrating environmental considerations into both new and existing infrastructure projects. For example, new approaches and ideas in the space of biodiversity-sensitive urban design aim to create urban environments that make a positive contribution to biodiversity—biophilic urbanism. We could start thinking on biophilic road planning, to include biodiversity and environmental values from the start. This interdisciplinary approach is vital for addressing the complex challenges posed by road infrastructure and ensuring a sustainable coexistence between development and biodiversity conservation.

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