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EDITORIAL

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Ecological Solutions for Linear Infrastructure Networks: The key to green infrastructure development

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Introduction

The rapid expansion of linear infrastructure networks poses a global threat to biodiversity and ecosystem services (Laurance and Balmford 2013; van der Ree et al. 2015). Over the last few decades, research and careful planning have led to solutions which begin mitigating the negative effects of these infrastructures (Lesbarrères and Fahrig 2012; van der Grift et al. 2013; Rytwinski et al. 2016). Transport monitoring protocols

and data are becoming more widely available, and novel actions are being tested and promoted (Vercayie and Herremans 2015; Schwartz et al. 2020). Robust protocols, landscape genetics, ecological connectivity modeling, remote sensing including GPS animal tracking, among other tools, are being frequently used in infrastructure planning and management (Balkenhol and Waits 2009; Carvalho et al. 2018; Shilling et al. 2020; Valerio et al. 2020; Zeller et al. 2020). The approach towards linear infrastructure planning is also transforming. Linear infrastructure-related habitats are increasingly valued for the biodiversity conservation opportunity they provide and have become a key contributor to Green Infrastructure development (Dániel-Ferreira et al. 2020; Ouédraogo et al. 2020). There is also a growing awareness of the need for coexistence between infrastructure and biodiversity, and citizens participate in this process (Périquet et al. 2018; Waetjen and Shilling 2018).

IENE (Infrastructure & Ecology Network Europe) is a network of experts on linear infrastructures (LI) and biodiversity from Europe and across the world. The main aim of IENE is to provide a platform to promote cross-boundary cooperation in research, mitigation and planning of LI (Seiler and Helldin 2015), facilitated by frequent national and international meetings. IENE organizes an international conference every two years, focusing on biodiversity and transportation (IENE 2021). These conferences provide a way to present innovative research, identify critical questions and problems, discuss ways to increase the efficiency of solutions, and improve communication among decision makers, planners, and researchers. IENE is also a founding member of the Global Congress on Linear Infrastructure and Environment, which brings together experts from every continent to discuss globally important issues of the interaction between linear infrastructure and the environment. Furthermore, IENE, together with other international transport and ecology conference organizations, the World Wide Fund for Nature (WWF) and the International Union for Conservation of Nature (IUCN), has helped to develop The Global Strategy for Ecologically Sustainable Transport and other Linear Infrastructure, a strategy to support biodiversity conservation and enhance ecological connectivity at the governance, policies, planning and implementation stages of transport projects around the world (Georgiadis et al. 2020).

The IENE2020 International Conference "LIFE LINES – Linear Infrastructure Networks with Ecological Solutions" aimed to improve environmental sustainability of infrastructure by bringing together and sharing the experiences of experts involved in the planning, research and administration of linear infrastructures around the world. The Conference focused on transportation infrastructures, but it also included other linear infrastructures, such as electric power lines. The Conference was held online from 12 to 14 January 2021, and was organized by the University of Évora, LIFE LINES project (LIFE14 NAT/PT/001081 https://lifelines.uevora.pt/), and IENE. The Conference was attended by over 300 participants from 31 countries, representing different stakeholders including ecologists, road and linear infrastructure technicians, NGOs, and policymakers. Participations were highly diverse, with 197 presentations, 13 workshops and two side events (LIFE SAFE CROSSING

workshop and LIFE LINES Final Seminar), covering several important topics such as: (1) Innovative Solutions for Linear Infrastructure Impact assessment, Mitigation and Monitoring; (2) Challenges and Opportunities for Infrastructure-Related Habitats; (3) Linear Infrastructure Ecology; (4) Citizen Science and the Involvement of Civil Society; and (5) Legislation and Policy (IENE 2020 Organising and Programme committees, 2021).

About this collection

This Special Issue, entitled "Linear Infrastructure Networks with Ecological Solutions", is a collection of studies that address the main themes of the IENE 2020 conference. Fifteen papers in this volume present research carried out on linear infrastructures, namely roads (8 papers), railways (1 paper), roads and railways (3 papers), power lines (2 papers) and waterways (1 paper). These meaningful contributions were brought from Europe (11 papers), South America (1 paper), North America (2 papers) and Asia (1 paper), and discuss legislation and policy, wildlife-mortality patterns, citizen science, barrier effects, mitigation planning and testing the efficiency of mitigation.

Important insights on **legislation and policy** are highlighted by experiences from Germany and the Carpathians. Steege et al. (2022) present us with a review of projects, political programmes, and progressive legislation on German federal waterways. While, Papp et al. (2022) provide specific recommendations to mainstream ecological connectivity into the planning and design of linear transport infrastructure to maintain the long-term viability of large carnivores in the Carpathians region. These studies contribute with guidance for other authorities striving towards similar goals.

The patterns of **wildlife mortality on roads (roadkill)** were assessed in Brazil, India and Greece. The roadkill of four mammal species were related with landscape use in Brazil. Generalist species such as the crab-eating fox (*Cerdocyon thous*) and the six-banded armadillo (*Euphractus sexcinctus*), showed higher roadkill probabilities in human-modified regions; however, habitat specialist mammals, such as the giant anteater (*Myrmecophaga tridactyla*) and the collared-anteater (*Tamandua tetradactyla*), showed higher roadkill risk with increasing fragmentation of forest or savanna areas, respectively (Cirino et al. 2022). From India, Sur et al. (2022) present the first patterns of vertebrate roadkill assessed in a National Park, demonstrating that roadkill rates were highest during the monsoon season, particularly for amphibians. The analysis of long-term mortality of the brown bear (*Ursus arctos*) in Greece revealed 60% of roadkills were concentrated in four hotspots, occurring most often in periods of increased animal mobility, under poor light conditions and reduced visibility (Psaralexi et al. 2022). All of these results are crucial for identifying the risk to different taxonomic groups, and defining proper mitigation measures specific to each region and communities.

There is an interesting contribution from a **citizen science** project from Belgium, which collected almost 90,000 roadkill records in 12 years. Although collected roadkill data was biased towards larger and more charismatic species, the data suggests that the number of roadkill is decreasing in recent years (Swinnen et al. 2022). This contribution highlights the benefit of getting the public to actively participate in biodiversity conservation.

The role of species behaviour on the **barrier effect of roads** was studied in Portugal. Roads were a behavioural barrier to the movement of small-sized carnivores, although they also take advantage of road proximity as feeding areas (Ferreira et al. 2022). In another study, Fernandes et al. (2022) also found Cabrera voles (*Microtus cabrerae*), an endangered small mammal, had different space use and movement patterns when living on road verges compared to living away from the road. Both studies highlight the need to integrate species behaviour into road permeability projects.

There were also novel approaches to inform **mitigation planning** on roads, railways and powerlines. Helldin (2022) discusses the advantages and disadvantages of single large crossing structures versus several small crossing structures for decreasing barrier effects of roads and railways on wildlife. This debate is of utmost importance as this knowledge improves the efficiency of mitigation planning and the communication between environmental planners and transport agencies. Bird distribution data was used in spatial models to derive a high-resolution map of risks of collisions between birds and power lines across Belgium, identifying locations where mitigation measures should be placed (Paquet et al. 2022). Both of the above approaches can be applied to different contexts, improving spatial planning and design for mitigation across linear infrastructure networks.

The final theme of the papers in this collection focuses on the **effectiveness of mitigation measures,** giving practical recommendations on specific strategies. Accommodating co-use by wildlife and humans may be possible when the mammal species are tolerant of human presence; however, wildlife passages intended to be used by species that are sensitive to human presence should avoid human co-use (Warnock-Juteau et al. 2022). Commonly implemented wire netting fences are not efficient at stopping small animals from climbing over and onto the roadway, thus fences made of alternative materials (e.g., concrete, PVC) may be more efficient (Conan et al. 2022). Short fencing segments can increase the risk of Florida Key deer (*Odocoileus virginianus clavium*) vehicle collisions, especially near fence-ends, thus mitigation measures must be implemented on an appropriate scale to be effective (Huijser and Begley 2022). Wildlife warning reflectors are not an effective method to modify roe deer (*Capreolus capreolus*) behaviour and reduce risk of wildlife-train collisions (Jasińska et al. 2022). Similar results were found from deflectors used to reduce bird-power line collisions (Kornhuber et al. 2022). These authors recommend the use of the animal deflector to a polymeric insulator, since no danger to small birds and small animals could be identified. However, more research and tests on different insulator types need to be conducted before solid recommendations can be made. Testing of mitigation strategies allows for their limitations to be identified and provides a foundation for improving the techniques.

Conference conclusions

The IENE 2020 International Conference presented the impacts and opportunities that Linear Infrastructure brings to nature conservation, allowed the discussion of successes and failures in mitigation and monitoring, and showed novel approaches to harmonize infrastructures and the surrounding environment. The contents of this volume underlines how important ecological solutions are to minimize the negative impacts of Linear Infrastructure and to achieve increasingly greener infrastructures.

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References

Balkenhol N, Waits LP (2009) Molecular road ecology: Exploring the potential of genetics for investigating transportation impacts on wildlife. Molecular Ecology 18(20): 4151–4164. https://doi.org/10.1111/j.1365-294X.2009.04322.x

Carvalho F, Lourenço A, Carvalho R, Alves PC, Mira A, Beja P (2018) The effects of a motorway on movement behaviour and gene flow in a forest carnivore: Joint evidence from road mortality, radio tracking and genetics. Landscape and Urban Planning 178: 217–227. https://doi.org/10.1016/j.landurbplan.2018.06.007

Cirino DW, Lupinetti-Cunha A, Freitas CH, de Freitas SR (2022) Do the roadkills of different mammal species respond the same way to habitat and matrix? In: Santos S, Grilo C, Shilling F, Bhardwaj M, Papp CR (Eds) Linear Infrastructure Networks with Ecological Solutions. Nature Conservation 47: 65–85. https://doi.org/10.3897/natureconservation.47.73010

Conan A, Fleitz J, Garnier L, Le Brishoual M, Handrich Y, Jumeau J (2022) Effectiveness of wire netting fences to prevent animal access to road infrastructures: an experimental study on small mammals and amphibians. In: Santos S, Grilo C, Shilling F, Bhardwaj M, Papp CR (Eds) Linear Infrastructure Networks with Ecological Solutions. Nature Conservation 47: 271–281. https://doi.org/10.3897/natureconservation.47.71472

Dániel-Ferreira J, Bommarco R, Wissman J, Öckinger E (2020) Linear infrastructure habitats increase landscape-scale diversity of plants but not of flower-visiting insects. Scientific Reports 10(1): e21374. https://doi.org/10.1038/s41598-020-78090-y

Fernandes N, Ferreira EM, Pita R, Mira A, Santos SM (2022) The effect of habitat reduction by roads on space use and movement patterns of an endangered species, the Cabrera vole *Microtus cabrerae*. In: Santos S, Grilo C, Shilling F, Bhardwaj M, Papp CR (Eds) Linear Infrastructure Networks with Ecological Solutions. Nature Conservation 47: 177–196. https://doi.org/10.3897/natureconservation.47.71864

Ferreira EM, Valerio F, Medinas D, Fernandes N, Craveiro J, Costa P, Silva JP, Carrapato C, Mira A, Santos SM (2022) Assessing behaviour states of a forest carnivore in a road-dominated landscape using Hidden Markov Models. In: Santos S, Grilo C, Shilling F, Bhardwaj M, Papp CR (Eds) Linear Infrastructure Networks with Ecological Solutions. Nature Conservation 47: 155–175. https://doi.org/10.3897/natureconservation.47.72781

Georgiadis L, et al. (Coord.) (2020) A Global Strategy for Ecologically Sustainable Transport and other Linear Infrastructure. IENE, ICOET, ANET, ACLIE, WWF, IUCN, Paris, 24 pp. https://www.iene.info/content/uploads/2020Dec_TheGlobalStrategy90899.pdf

Helldin JO (2022) Are several small wildlife crossing structures better than a single large? Arguments from the perspective of large wildlife conservation. In: Santos S, Grilo C, Shilling F, Bhardwaj M, Papp CR (Eds) Linear Infrastructure Networks with Ecological Solutions. Nature Conservation 47: 197–213. https://doi.org/10.3897/natureconservation.47.67979

Huijser MP, Begley JS (2022) Implementing wildlife fences along highways at the appropriate spatial scale: A case study of reducing road mortality of Florida Key deer. In: Santos S, Grilo C, Shilling F, Bhardwaj M, Papp CR (Eds) Linear Infrastructure Networks with Ecological Solutions. Nature Conservation 47: 283–302. https://doi.org/10.3897/natureconservation.47.72321

IENE (2020) Organising and Programme committees 2021. IENE 2020 International Conference – LIFE LINES – Linear Infrastructure Networks with Ecological Solutions. Abstract Book. January 12–14, 2021, Universidade de Évora. https://www.iene2020.info/index.html

IENE (2021) IENE Infrastructure & Ecology Network Europe. https://www.iene.info/iene/iene-today/

Jasińska KD, Babińska-Werka J, Krauze-Gryz D (2022) A test of wildlife warning reflectors as a way to reduce risk of wildlife-train collisions. In: Santos S, Grilo C, Shilling F, Bhardwaj M, Papp CR (Eds) Linear Infrastructure Networks with Ecological Solutions. Nature Conservation 47: 303–316. https://doi.org/10.3897/natureconservation.47.73052

Kornhuber S, Pampel H-P, Görlich J, Leiblein-Wild M, Jöckle C (2022) Preliminary results on the bird protection effectiveness of animal deflectors on railway overhead lines based on electrical current evaluation. In: Santos S, Grilo C, Shilling F, Bhardwaj M, Papp CR (Eds) Linear Infrastructure Networks with Ecological Solutions. Nature Conservation 47: 317–333. https://doi.org/10.3897/natureconservation.47.70704

Laurance WF, Balmford A (2013) Land use: A global map for road building. Nature 495(7441): 308–309. https://doi.org/10.1038/495308a

Lesbarrères D, Fahrig L (2012) Measures to reduce population fragmentation by roads: What has worked and how do we know? Trends in Ecology & Evolution 27(7): 374–380. https://doi.org/10.1016/j.tree.2012.01.015

Ouédraogo DY, Villemey A, Vanpeene S, Coulon A, Azambourg V, Hulard M, Guinard E, Bertheau Y, Flamerie De Lachapelle F, Rauel V, Le Mitouard E, Jeusset A, Vargac M, Witté

I, Jactel H, Touroult J, Reyjol Y, Sordello R (2020) Can linear transportation infrastructure verges constitute a habitat and/or a corridor for vertebrates in temperate ecosystems? A systematic review. Environmental Evidence 9(1): e13. https://doi.org/10.1186/s13750-020-00196-7

Papp C-R, Dostál I, Hlaváč V, Berchi GM, Romportl D (2022) Rapid linear transport infrastructure development in the Carpathians: A major threat to the integrity of ecological connectivity for large carnivores. In: Santos S, Grilo C, Shilling F, Bhardwaj M, Papp CR (Eds) Linear Infrastructure Networks with Ecological Solutions. Nature Conservation 47: 35–63. https://doi.org/10.3897/natureconservation.47.71807

Paquet J-Y, Swinnen K, Derouaux A, Devos K, Verbelen D (2022) Sensitivity mapping informs mitigation of bird mortality by collision with high-voltage power lines. In: Santos S, Grilo C, Shilling F, Bhardwaj M, Papp CR (Eds) Linear Infrastructure Networks with Ecological Solutions. Nature Conservation 47: 215–233. https://doi.org/10.3897/natureconservation.47.73710

Périquet S, Roxburgh L, le Roux A, Collinson W (2018) Testing the value of citizen science for roadkill studies: A case study from South Africa. Frontiers in Ecology and Evolution 6: e15. https://doi.org/10.3389/fevo.2018.00015

Psaralexi M, Lazarina M, Mertzanis Y, Michaelidou D-E, Sgardelis S (2022) Exploring 15 years of brown bear (*Ursus arctos*)-vehicle collisions in northwestern Greece. In: Santos S, Grilo C, Shilling F, Bhardwaj M, Papp CR (Eds) Linear Infrastructure Networks with Ecological Solutions. Nature Conservation 47: 105–119. https://doi.org/10.3897/natureconservation.47.71348

Rytwinski T, Soanes K, Jaeger JAG, Fahrig L, Findlay CS, Houlahan J, van der Ree R, van der Grift EA (2016) How effective is road mitigation at reducing road-kill? A meta-analysis. PLoS ONE 11(11): e0166941. https://doi.org/10.1371/journal.pone.0166941

Schwartz ALW, Shilling FM, Perkins SE (2020) The value of monitoring wildlife roadkill. European Journal of Wildlife Research 66(1): e18. https://doi.org/10.1007/s10344-019-1357-4

Seiler A, Helldin J-O (2015) Greener transport infrastructure – IENE 2014 International Conference. In: Seiler A, Helldin J-O (Eds) Proceedings of IENE 2014 International Conference on Ecology and Transportation, Malmö, Sweden. Nature Conservation 11: 5–12. https://doi.org/10.3897/natureconservation.11.5458

Shilling F, Collinson W, Bil M, Vercayie D, Heigl F, Perkins SE, MacDougall S (2020) Designing wildlife-vehicle conflict observation systems to inform ecology and transportation studies. Biological Conservation 251: 108797. https://doi.org/10.1016/j.biocon.2020.108797

Steege V, Engelbart D, Hädicke NT, Schäfer K, Wey JK (2022) Germany's federal waterways – A linear infrastructure network for nature and transport. In: Santos S, Grilo C, Shilling F, Bhardwaj M, Papp CR (Eds) Linear Infrastructure Networks with Ecological Solutions. Nature Conservation 47: 15–33. https://doi.org/10.3897/natureconservation.47.70732

Sur S, Saikia PK, Saikia MK (2022) Speed thrills but kills: A case study on seasonal variation in roadkill mortality on National Highway 715 (new) in Kaziranga-Karbi Anglong Landscape, Assam, India. In: Santos S, Grilo C, Shilling F, Bhardwaj M, Papp CR (Eds) Linear Infrastructure Networks with Ecological Solutions. Nature Conservation 47: 87–104. https://doi.org/10.3897/natureconservation.47.73036

Swinnen KRR, Jacobs A, Claus K, Ruyts S, Vercayie D, Lambrechts J, Herremans M (2022) 'Animals under wheels': Wildlife roadkill data collection by citizen scientists as a part of their nature recording activities. In: Santos S, Grilo C, Shilling F, Bhardwaj M, Papp CR (Eds) Linear Infrastructure Networks with Ecological Solutions. Nature Conservation 47: 121–153. https://doi.org/10.3897/natureconservation.47.72970

Valerio F, Ferreira E, Godinho S, Pita R, Mira A, Fernandes N, Santos SM (2020) Predicting Microhabitat Suitability for an Endangered Small Mammal Using Sentinel-2 Data. Remote Sensing 12(3): e562. https://doi.org/10.3390/rs12030562

van der Grift EA, van der Ree R, Fahrig L, Findlay S, Houlahan J, Jaeger JAG, Klar N, Madriñan LF, Olson L (2013) Evaluating the effectiveness of road mitigation measures. Biodiversity and Conservation 22(2): 425–448. https://doi.org/10.1007/s10531-012-0421-0

van der Ree R, Smith DJ, Grilo C (2015) The Ecological Effects of Linear Infrastructure and Traffic: Challenges and Opportunities of Rapid Global Growth. In: van der Ree R, Smith DJ, Grilo C (Eds) Handbook of Road Ecology. John Wiley and Sons. https://doi.org/10.1002/9781118568170

Vercayie D, Herremans M (2015) Citizen science and smartphones take roadkill monitoring to the next level. In: Seiler A, Helldin J-O (Eds) Proceedings of IENE 2014 International Conference on Ecology and Transportation, Malmö, Sweden. IENE 2014. Nature Conservation 11: 29–40. https://doi.org/10.3897/natureconservation.11.4439

Waetjen DP, Shilling FM (2018) Large extent volunteer roadkill and wildlife observation systems as sources of reliable data. Frontiers in Ecology and Evolution 6: e84. https://doi.org/10.3389/fevo.2017.00089

Warnock-Juteau K, Bolduc V, LoScerbo D, Anderson M, Daguet C, Jaeger JAG (2022) Co-use of existing crossing structures along roads by wildlife and humans: Wishful thinking? In: Santos S, Grilo C, Shilling F, Bhardwaj M, Papp CR (Eds) Linear Infrastructure Networks with Ecological Solutions. Nature Conservation 47: 235–270. https://doi.org/10.3897/natureconservation.47.73060

Zeller KA, Wattles DW, Destefano S (2020) Evaluating methods for identifying large mammal road crossing locations: Black bears as a case study. Landscape Ecology 35(8): 1799–1808. https://doi.org/10.1007/s10980-020-01057-x