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Rapid linear transport infrastructure development in the Carpathians: A major threat to the integrity of ecological connectivity for large carnivores

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Abstract

The development of sustainable transport is a key challenge in societies where there is an accelerated need for socio-economic development. This is the case for seven countries from central and south-eastern Europe that share the Carpathian Mountains. The challenge of developing sustainable transport requires transdisciplinary, or at least cross-sectoral cooperation, between the transport development and nature conservation sectors. Such cooperation is not in the culture of the Carpathian countries, which together host some of the most remarkable biodiversity values in Europe, including the largest populations of brown bear, grey wolf and Eurasian lynx. The overall length of motorways in these countries more than quintupled in the last 30 years and the rapid expansion of Linear Transport Infrastructure (LTI) continues at exacerbating rates. The rich biodiversity habitats are being fragmented and the concept of ecological connectivity is poorly understood and implemented by the national authorities. Ecological networks for large carnivores are not defined nor officially recognised in the Carpathian countries, with little exceptions. The legislation is not consistent across the strands of ecological connectivity and is not harmonised between the countries to effectively support transnational conservation efforts. Thus, the critical intersections between planned or even existing LTI and ecological corridors for large carnivores cannot be identified, in most cases leading to increasing habitat fragmentation and isolation of wildlife populations in the region. We summarised all this key context-related information for the Carpathians in relation to LTI development and ecological connectivity. To counteract this trend in the Carpathian ecoregion, we propose a set of recommendations to: improve and harmonise the legislation; develop and endorse methodologies for designating ecological corridors; address the cumulative impact on ecological connectivity; define other threats on landscape permeability; improve stakeholder engagement, cooperation and communication; develop comprehensive and transparent biodiversity and transport databases; monitor wildlife and transport for implementing most appropriate mitigation measures and strategies; build capacity to address the issue of sustainable transportation; and foster transnational cooperation and dialogue. Bringing these elements together will support the design of ecological networks in a way that considers the needs and location of both current and future habitats and contribute to efforts to address the climate crisis. These specific recommendations are relevant also for other areas of the world facing similar problems as the Carpathians.

Keywords

Connectivity conservation, conservation, ecological corridors, environmental impact, habitat fragmentation, large mammals, LTI, policy actions, sustainable transport

Introduction

Habitat loss and fragmentation is considered as one of the main causes of biodiversity loss worldwide (Rands et al. 2010; Barnosky et al. 2011; Hilty et al. 2020), threatening with extinction over a quarter of the world's mammalian species (Butchart et al. 2010), including large carnivores (Noss et al. 1996; Crooks 2002; Crooks et al. 2017). Habitat fragmentation usually refers to a landscape-scale process of transforming a large and continuous habitat into smaller patches of different sizes, spatially separated from each other by a matrix of generally human-modified land use types (Wilcove et al. 1986; Fahrig 2003; Rogan and Lacher 2018) and it involves habitat loss, deterioration and subdivision (see Fischer and Lindenmayer 2007).

The development of linear transport infrastructures (LTI) and networks are one of the main reasons for habitat fragmentation (Geneletti 2003, 2004; Trocmé et al. 2003; Rhodes et al. 2014), particularly in mountain areas and it negatively affects large carnivores (Forman and Alexander 1998; Fahrig and Rytwinski 2009; Morales-González et al. 2020) not only at local, but also at landscape level (Proctor et al. 2012; Bischof et al. 2017; Finďo et al. 2018). Large LTI are usually overlapping, altering or sometimes even interrupting wildlife/ecological corridors, especially if the infrastructures are not permeable, in the absence of properly designed and placed underpasses, overpasses and other crossing structures (Van der Ree et al. 2009). Considerable efforts are, thus, being made to maintain ecological connectivity at the landscape level (Hilty et al. 2019; Keeley et al. 2019) in order to allow species movement. Dedicated ecological connectivity studies are needed in this respect (Loro et al. 2015; Mimet et al. 2016) and to integrate their results into early planning processes.

In the mountainous areas of North America, western or northern Europe, LTI mitigation is more commonly implemented (Van der Grift et al. 2013) than in the Carpathian ecoregion. Moreover, differences exist in implementation of LTI between the eastern and western part of the Carpathians. This is mainly due to the political and institutional past and socio-economic differences between the countries of the Carpathian ecoregion.

The lower development of LTI and the relatively smaller human pressure, in general, in the Carpathians, compared to, for example, western Europe, supports the greatest populations of large carnivores in Europe, outside Russia (Chapron et al. 2014). However, habitat fragmentation started to increase lately across the whole Carpathians because of the growing and legitimate need for socio-economic development (Hlaváč et al. 2019) and is likely to affect the large carnivore species that are present in the ecoregion, namely the brown bear (*Ursus arctos* L.), grey wolf (*Canis lupus* L.) and the Eurasian lynx (*Lynx lynx* L.). This is already reflected in the overall length of motorways developed in the Carpathian countries which more than quintupled in the last three decades. This dramatically increased building of road infrastructure in the region, with further infrastructure to be planned or rapidly expanded and/or upgraded, is happening without implementation of suitable mitigation measures. The main reason is a long-term negligence of wildlife-traffic-collision problems in the past, absence of studies on wildlife movement and absence of proper ecological assessment in the area of planned infrastructure. It is absolutely necessary to plan and implement wildlife mitigation measures on planned roads/railways (Fedorca et al. 2019) and also enhance migration permeability during the upgrading process of existing ones.

Our focus in the paper is to document the negative effects of LTI on wildlife, more specifically on the ecological corridors in the Carpathian ecoregion (as the area of interest) used by the large carnivores present here. We selected this group of animals as focus species, considering that we gathered data and knowledge related to it in conjunction with transport in a systematic way from 2017 to 2021 through different conservation projects. Last but not least, large carnivores are umbrella species and their conservation brings benefits to several other large mammals and vertebrates in general (Hlaváč et al. 2019).

The aim of the paper is to provide a comprehensive review of the LTI development (as grey infrastructure), ecological corridors conservation (as part of green infrastructure) and solutions for harmonising grey and green infrastructure in the Carpathians. These two fields, transportation and nature conservation, need concrete policy actions for their reconciliation and we sought to provide the basis for this in the region.

We provide a brief overview of: (1) the Carpathian ecoregion to better understand the regional context, (2) relevant legislation governing nature conservation and transport infrastructure development, (3) status of transport infrastructure in the region, (4) key ecological aspects including status of ecological connectivity and identification of ecological corridors for large carnivores, (5) effects of current road and rail transportation on ecological corridors in the Carpathians, (6) positive and negative examples of transport infrastructure development in the Carpathians and (7) knowledge, practice and other gaps in avoiding fragmentation by transport infrastructure development. Furthermore, we propose a set of recommendations to maintain ecological connectivity while developing transport infrastructure in the Carpathians, which are also applicable in other areas of the world with similar problems.

Methods

We collected information on projects and studies/reports carried out on our topics of interest especially in the Carpathian ecoregion. Qualitative research of data and information was sought for exploring and synthesising the key results obtained in previously conducted relevant research and nature conservation projects and activities.

Datasets on transport and biodiversity have also been gathered and databases investigated and interrogated to select the most appropriate pieces of information. We reviewed the most relevant legislation in connection with biodiversity conservation, ecological connectivity, strategic environmental assessment, environmental impact assessment, appropriate assessment, spatial planning etc. at European, Carpathian and national levels.

The main source of information related to transport infrastructure and ecological corridors in the Carpathians originated from the TRANSGREEN (DTP1-187-3.1), ConnectGREEN (DTP2-072-2.3) and SaveGREEN (DTP3-314-2.3) projects (e.g. Hlaváč et al. 2019; Papp and Berchi 2019; Okániková et al. 2021), which first addressed, in a systematic way, the overlapping between LTI development and connectivity conservation in this region.

To complete the picture of transport development and ecological connectivity at the national levels, as well as to provide country-specific information regarding different practices, stakeholder engagement in the form of meetings was carried out.

The most relevant international and scientific literature available regarding our topics of interest was consulted, in order to better understand and position the Carpathian issues, in relation to the global context. In this respect, we searched for publications in databases/research tools, such as Web of Science, Scopus, CrossRef, Google Scholar etc. We used the following keywords and combinations: habitat fragmentation, linear transport infrastructure, transport infrastructure and ecological connectivity, threats to ecological connectivity, conservation of large carnivores, ecological connectivity and large carnivores. We searched the 1960–2021 interval and we considered the most cited and newest articles of interest as main conditions/criteria.

Maps were developed using ArcGIS 10 (ESRI 2011) by collecting and integrating data from both reliable literature and results generated through the TRANSGREEN, ConnectGREEN and SaveGREEN projects.

Results and discussion

The Carpathian ecoregion

The importance and vulnerability of the Carpathian mountains

Mountain environments cover only about 25% of the total land area on the globe, but are shelter to over 85% of the planet's species of, for example, amphibians, birds and mammals, many of them being restricted to mountains. Mountains play a multitude of roles for Earth's biodiversity and influence surrounding lowlands through biotic interchange, changes in regional climate and nutrient runoff (Rahbek et al. 2019a, 2019b). They occur in half of the world's biodiversity hotspots (Jacobs et al. 2021).

Climate change is affecting the mountain ecosystems at a faster rate than other terrestrial ecosystems (Jacobs et al. 2021) and temperature rises tend to be positively correlated with elevation (Pepin et al. 2015) and is expected to be more prevalent in the northern latitudes (Nogués-Bravo et al. 2007). The Carpathian Mountains are included in this trend, being exposed to multiple other stressors besides climate change that can affect the exceptional biodiversity values present here, especially the rapid expansion of LTI and other types of infrastructure.

The Carpathian ecoregion (Fig. 1) covers 209,256 km^2 (CERI 2001) and is shared by seven countries: Czech Republic, Slovakia, Poland, Hungary, Ukraine, Romania and Serbia. The studies on climate change affecting biodiversity in the Carpathians are scarce (Gurung et al. 2009; Werners et al. 2014a, 2014b; Hlásny et al. 2016; Kruhlov et al. 2018) and the combined effects of both climate change and habitat fragmentation due to LTI development has not been addressed and quantified yet.

Our broader focus on the Carpathian ecoregion is relevant in the context of large carnivores' conservation, considering their need for extensive territories on one hand and, on the other, of LTI development which is more prevalent in the lower lands of the Carpathians.

Natural values and geography

Thanks to their exceptional natural values, including a great variety of endemic plants and animals, but also vulnerability, the Carpathians are included in WWF's "Global 200" list of major ecoregions in need of biodiversity and habitat conservation (WWF 2001).

More than 60,000 native species, excluding microorganisms, are estimated to be present in the Carpathians (UNEP 2007). The Carpathians are home to approximately 4,000 vascular plants (Tasenkevich 1998), 35,000 invertebrate species, mainly insects, soil mites and spiders and over 500 vertebrate taxa, including mammals, nesting birds, amphibians, reptiles and fish and lampreys (UNEP 2007).

Three out of the five large carnivore species from Europe are present in the Carpathian ecoregion, namely the brown bear (*Ursus arctos*), grey wolf (*Canis lupus*) and the Eurasian lynx (*Lynx lynx*) (CERI 2001; UNEP 2007). Chapron et al. (2014) estimated 7,200 brown bears, 3,000 grey wolves and 2,300–2,400 Eurasian lynxes. Currently the overall size of these large carnivore populations in the Carpathians might be higher as a result of different conservation efforts and projects implemented in the region, as well as of favourable legislative framework at the EU level. Considering that these species are sensitive to habitat fragmentation caused by LTI (Proctor et al. 2012; Bischof et al. 2017; Finďo et al. 2018) and need extensive territories to satisfy their needs, concrete and intensive conservation efforts and harmonised management measures need to be put into action in the Carpathian ecoregion in a concerted way (Papp et al. 2020).

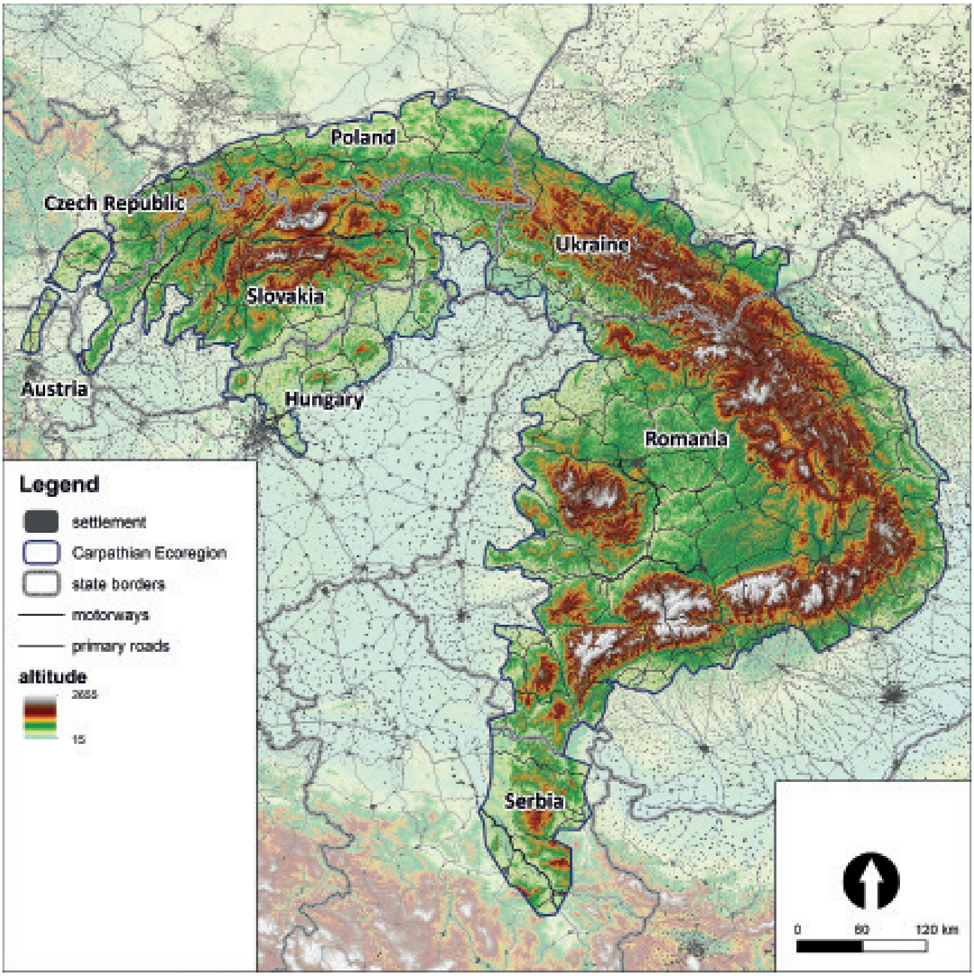

Figure 1. The Carpathian ecoregion.

The Carpathians have a length of 1,500 m, an average altitude of 850 m, the highest parts being in the northwest and south, with the greatest elevation in Slovakia, 2,655 m (UNEP 2007).

Rising temperatures have been recorded in all seasons for the period 1961–2010, with substantial warming of up to 2.4 °C in summer seasons and the model projections suggest a future temperature increase of up to 1.8 °C for 2021–2050 (EEA 2017).

The Carpathians are an important water source for three major rivers, namely the Danube and Dniester, flowing into the Black Sea and the Vistula River, flowing into the Baltic Sea.

The Carpathians are not only home to wildlife, but also to over 17 million people living in both small remote villages and major cities (UNEP 2007).

As a result of the political transformation of 1989, accelerated changes in land-use and land-cover started to occur in Central and Eastern Europe, especially due to profound changes in agriculture, improvements in people's welfare, growth in the tertiary sector and migration from rural to urban areas (Turnock 2003). Farmland abandonment increased in this period most probably in relation to institutional changes and restructuring of property rights (Munteanu et al. 2017). In addition, farmland abandonment in the Carpathian region threatens cultural landscapes and their associated biodiversity, although this can, in turn, increase carbon sequestration (Kuemmerle et al. 2008).

Relevant legislation for ecological connectivity in the Carpathians

Relevant legislation at international level and implications for the Carpathian countries

The first European nature conservation convention, the Bern Convention, signed in 1979, is the European contribution to the sustainable conservation of the world's biodiversity. The Bern Convention developed the Emerald Network, a group of selected natural areas hosting crucial and threatened biodiversity in Europe (CoE 2021).

The contribution of EU member states to the pan-European Emerald Network is represented by the creation and management of the Natura 2000 Network (European Commission 1992, 2009), which is the largest coordinated network of protected areas in the world (EEA 2021). However, the Natura 2000 Network is only applicable in the EU member states, meaning that, in the Carpathian region, it is the main conservation tool in Czech Republic, Slovakia, Poland, Hungary and Romania (Fig. 2). A total of 1,178 Natura 2000 sites were designated by these countries in their Carpathian Mountain area. In the other two non-EU Carpathian countries, Ukraine and Serbia, the Emerald Network is the key conservation instrument (Fig. 2), having 49 Emerald sites designated in their Carpathian area.

The European Commission (2021a) also promotes the conservation of the five large carnivore species found in Europe and its guiding documents are used by the Carpathian countries to improve their conservation efforts of the three species that are present in the area and to develop national action plans.

The EU's Biodiversity Strategy for 2030 (European Commission 2021b) is favouring both large carnivores and ecological connectivity conservation. The EU Strategy on Green Infrastructure is another EU-wide strategy relevant in the context of ecological connectivity and sustainable transport development.

The Convention on Environmental Impact Assessment (EIA) in a Transboundary Context or the ESPOO Convention, adopted in 1991, is another important legislative instrument. Given that seven nations share the Carpathian Mountain range and that large infrastructure projects including LTI are often developed between countries as part of different major transport corridors of international importance, the ESPOO can represent a valuable tool when mitigation measures, for instance, are not properly planned by a certain country, especially as a non-EU country.

The most important transport related policy of the European Commission (2021c) is the Trans-European Transport Network (TEN-T), directed towards the implementation and development of a Europe-wide network of roads, railway lines, inland waterways, maritime shipping routes, ports, airports and rail-road terminals. Three of the nine core transport network corridors are crossing the Carpathian area: Baltic Adriatic, Orient/East Mediterranean and Rhine-Danube (European Commission 2021d). The existing LTI, developed within these large transport corridors, is impacting to some extent the ecological connectivity in the Carpathian region. In the eastern part of the Carpathians, especially in Romania, the LTI, corresponding to the Orient/East Mediterranean and Rhine-Danube transport corridors, is still under development and concrete measures have to be taken in order to either avoid, mitigate or ultimately compensate for the potential environmental impacts.

The only multi-level governance mechanism covering the whole of the Carpathian area is the Framework Convention on the Protection and Sustainable Development of the Carpathians (Carpathian Convention), adopted in 2003 by the seven parties. It has two specifically relevant protocols to our topic: Protocol on Conservation and Sustainable Use of Biological and Landscape Diversity and Protocol on Sustainable

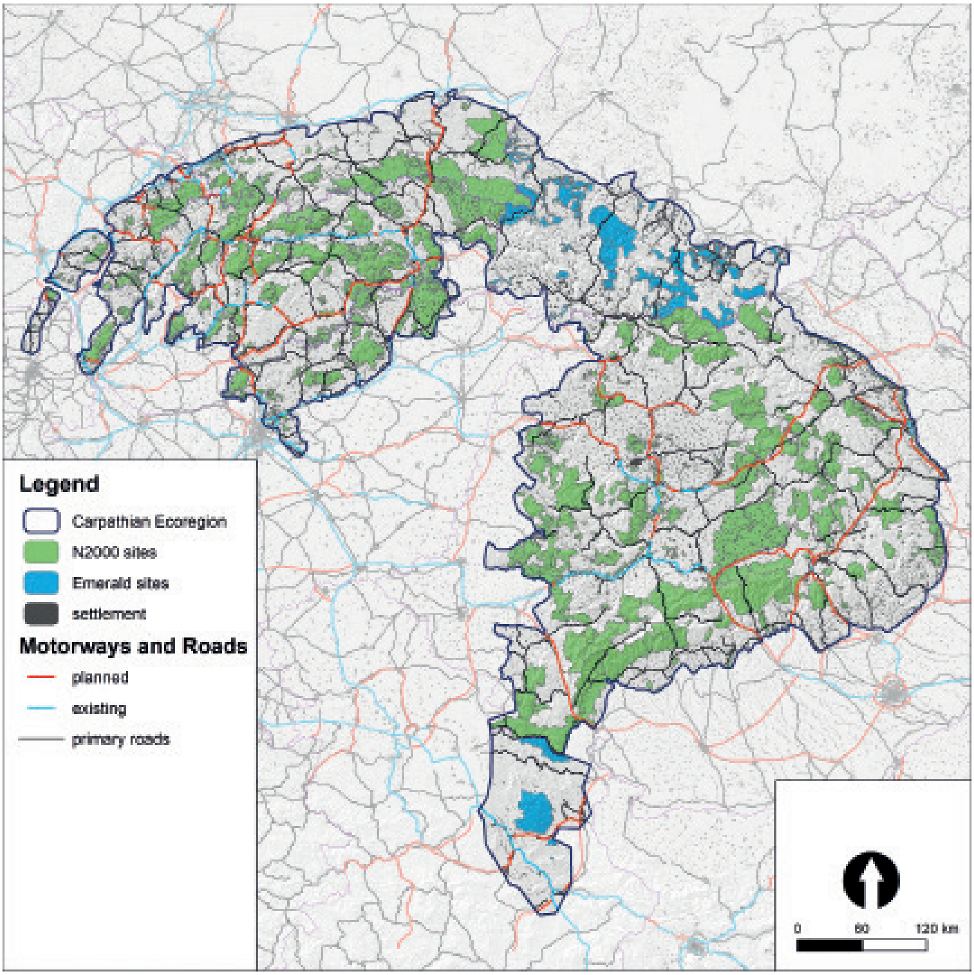

Figure 2. Natura 2000 and Emerald sites and transport network (motorways and roads) in the Carpathians.

Transport (UNEP Vienna Programme Office 2021). These two protocols set basically the framework for conserving biodiversity and maintaining ecological connectivity, while developing transport infrastructures in the Carpathians. In addition, the parties to the Carpathian Convention adopted the International Action Plan on Conservation of Large Carnivores and Ensuring Ecological Connectivity (Papp et al. 2020; UNEP Vienna Programme Office 2020), which is framing a unique and innovative example of a participatory and coordinated effort at transboundary level for implementing a population-based conservation of large carnivores, benefitting not only the Carpathians and the broader Danube Region, but also other regions in Europe and beyond. The second strategic objective of the Plan is to "Prevent habitat fragmentation and ensure ecological connectivity in the Carpathians" and contains a major action for mainstreaming biodiversity into transport planning and development.

Biodiversity and connectivity conservation is a priority action also under the macro-strategy European Strategy for the Danube region (EUSDR 2020), the Carpathians being part of the wider Danube region.

Relevant legislation at national levels related to ecological corridors

Since joining the EU, Czech Republic, Slovakia, Poland, Hungary and Romania gradually harmonised their national legislations with the EU regulations. Some of these countries (e.g. Czech Republic) have a higher level of compliance with EU legislation than others (e.g. Romania), at least from a transport and environmental point of view. On the other hand, the non-EU countries, namely Ukraine and Serbia, are preparing for this harmonisation as part of their EU accession process. This means that, in the Carpathian region, there are consistent differences in the national legislation from EU to non-EU countries, but there are also differences even within the same country category.

In all Carpathian countries, there is relevant nature conservation related legislation which provides the framework for conserving ecological corridors. However, all countries are lacking in official methodologies for the identification and designation of ecological corridors, which, in practice, makes connectivity conservation difficult and often ineffective.

Czech Republic and Slovakia are the most advanced countries in terms of connectivity conservation, where it is actually possible to protect ecological corridors and to maintain landscape connectivity through specific national nature conservation instruments.

In Hungary and Poland, there are also regulations regarding ecological corridors; however, the binding framework related to them is not well established, meaning that there are no uniform rules to determine corridors and there is no consistent network of corridors at the national level.

In Romania and Serbia, the protection and management of ecological corridors is not yet clearly defined, even though there are provisions related to the ecological network, including definitions. In practice, there are no legal obligations and restrictions imposed to secure ecological corridors. The only country in the Carpathians with a dedicated law on the preservation of the ecological network is Ukraine; however, its practical implementation is facing difficulties due to conflicting sectoral legislation or lack of dedicated funding for the identification of ecological corridors.

Papp and Berchi (2019) collected further information on the most relevant pieces of legislation at national levels in all the seven Carpathian countries.

In the absence of officially designated corridors, clear legal obligations and specific binding management measures to secure ecological connectivity, LTI development will remain one of the greatest threats to the integrity of natural habitats and functionality of existing ecological corridors in the Carpathians.

SEA, EIA, AA procedures and LTI planning in the Carpathians

The Strategic Environmental Assessment (SEA), Environmental Impact Assessment (EIA) and Appropriate Assessment (AA) can additionally contribute to a higher level of biodiversity and ecological connectivity protection by assessing the impact of different strategies, plans, programmes or projects on them.

The Directive on the assessment of the effects of certain plans and programmes on the environment (European Commission 2001), also known as the "SEA" Directive, requires and regulates the environmental assessment of certain plans and programmes which are likely to significantly harm the environment, for example, transport master plans. In the context of TEN-T further development and general transport planning, it is important to reconcile the descriptive and analytical aspects of the SEA and, in this respect, Fischer (2006) proposed a generic SEA framework for evaluating practice and developing further guidance.

The EIA Directive (European Commission 2014) on the assessment of the effects of certain public and private projects on the environment, requires environmental assessments for certain projects like LTI development, which can have a significant impact on the environment by virtue, before a development consent is given by the competent national authority.

AA is required by the Habitats Directive when a plan or project, either alone or in combination with other plans or projects, might impact a Natura 2000 site. The different LTI projects generally have an impact on Natura 2000 sites or other protected area categories, especially if developed in mountain areas like the Carpathians where there are several protected plant and animal species. AA is thus a prerequisite and shall constitute an integral part of SEA and EIA procedures.

The main issue in implementing the SEA, EIA or AA in the Carpathian countries is represented by the fact that the cumulative effect is not calculated properly or not at all. Several assessments of the effects of LTI on biodiversity conclude that there is no significant harm or provide a basic set of minimum mitigation measures and do not consider, for example, nearby electric fences, European road, railway and river (Fig. 3). In Romania, for instance, the ecological corridors are not identified and designated, so it is difficult to consider them in the planning process, which leads to an increase in habitat fragmentation.

In all Carpathian countries, based on previous experience in the construction of LTI, especially motorways, the greatest problems are seen in assessing the impact of the transport corridor on sustainable land development. In the Czech Republic, a key problem that is addressed is the impact of the new infrastructure on the environment, in particular, the elimination of health impacts (noise and vibrations, air pollution),

Figure 3. Cumulative impact of **a** highway sector between Turda and Aiud in Romania **b** Mureș River **c** railway **d** European road E81 and **e** electric fence used to keep wildlife away from the agricultural field, on the permeability of the landscape, not assessed.

the location of the linear construction in the landscape and the solution to the issue of fragmentation, the interruption of ecological corridors.

The benefits of taking an active and conscious part in shaping local spatial policies are generally not properly explained in the Carpathian countries and, therefore, low social awareness in the area of spatial planning and environmental protection can be observed, especially in Poland and Romania.

The problem of habitat fragmentation due to LTI has been underestimated in the Carpathian countries for a long time. In Slovakia, for instance, there are just a few studies aiming at the identification of core areas and ecological corridors. There is, indeed, an EIA analysis carried out during a landscape planning process, but it is rather a theoretical analysis lacking in reliable field data and validation, which is basically common to all Carpathian countries, excepting to some extent, Czech Republic. In Hungary, to regulate or decrease the impacts of LTI on natural habitats, the alignment is chosen in the planning stage, based on the least number of most sensitive areas each alternative is crossing.

In Serbia, as well as in Romania and Ukraine, generally there are no comprehensive habitat and species distribution maps which could provide a sound basis for integrative planning of LTI.

In Ukraine, there are specific provisions and recommendations to construct wildlife crossing structures and fences along certain roads, but they largely remain as recommendations, not as obligations.

In the absence of clear commitments to identify and designate ecological corridors in the Carpathians, many mitigation measures are not properly designed and certainly not implemented in proper places. Moreover, the lack of harmonisation of cross-sectoral policies and strategies is also leading to increased fragmentation in the region.

The evolution of transport infrastructure in the Carpathians

Ancient trade routes have crossed Europe since time immemorial. The Carpathian region is located at the crossroads of east–west (from south-eastern Europe/Asia towards western Europe) and north–south ("Amber road" Baltic-Adriatic). Therefore, the role of transport has always played a crucial role in the economic life of the Carpathian region. The complicated orography of the region predetermined the best routes for transport networks. Their directions followed the deep narrow valleys of main rivers embedded in mountain ranges. Other human activities were also concentrated in these favourable locations and formed barriers, which, in many cases, are hardly permeable for wildlife.

The 19th century laid the foundations for transport networks. Most of the region was under the rule of the Kingdom of Hungary in these times. The modern age country level transport network development concept was created and made official in 1848, which was designed to change the economic, social and political profile of the country. Besides improving the conditions of the most important inland waterways (Danube, Tisza, Dráva Rivers), it contained also the fundamental directives for the radial road and railway network (Oszter 2017).

Rail transportation reached its peak at the beginning of World War I (WWI). New post-WWI States faced the problem of a lack of infrastructure that was not designed to meet their needs, as the new geopolitical structure of Europe radically changed flows of trade and people in the region. The privileged position of railways began to decline in favour of the emerging road transport, which took over the role of main transport system during the 1960s. Its rising importance meant significant increase in motorisation and traffic intensities, which were difficult to be absorbed by existing road systems, especially in the hinterlands of main cities. The plans for the construction of motorway networks have been developed; for example, Czechoslovakia adopted it through a government resolution in 1963 (Lídl et al. 2009). However, the construction of the motorways in Carpathian countries continued very slowly. There were only 1,237

Table 1. Major road network in Carpathian countries and the projection to the future (CZ-Czech Republic, HU-Hungary, PL-Poland, RO-Romania, RS-Republic of Serbia, SK-Slovakia). Data source: MD ČR (2017); own GIS analysis, based on planning documents and maps from individual countries; the planned network figure is purely indicative, as many motorways are not yet spatially stabilised. ‡ In 1990, Czech and Slovak Republics were Czechoslovakia. § Czech Republic included 459 km of expressways into the motorway network from 1 January 2016. † Only part of Poland consisting of Voivodeships: Podkarpackie, Małopolskie, Śląskie and Świętokrzyskie.

	CZ	HU	PL†	RO	RS	SK
Motorways 1990 [km]	326‡	210	44	113	341	203‡
Motorways 2020 [km]	1.324§	1.253	538	904	925	497
Expressways 2020 [km]	373	474	216	-	32	244
Motorway and expressway density 2020 [km per 1000 km^2]	21.5	18.6	13.2	3.8	12.2	15.1
Planned motorways [km]	2.010	1.778	556	2.416	1.530	703
Planned expressways [km]	903	1.210	648	1.784	446	1.124
Density of complete planned network [km per 1000 km^2]	36.9	32.1	21.1	17.6	25.5	37.3
The network completion rate in 2020	58%	58%	63%	22%	48%	40%

kilometres of discontinuous motorway network in operation around 1990. Socio-economic changes after 1989 have brought an extremely rapid growth in traffic, which has spurred increased construction efforts; thus, the overall length of motorways in these countries more than quintupled in 30 years (see Table 1, Fig. 2). Further expansion is expected in upcoming years.

Key ecological aspects

Ecological connectivity, networks and corridors in the Carpathians

Ecological corridors are an important component of functional ecological networks and they primarily connect wildlife habitats and improve the functional connectivity of landscapes. Ecological connectivity, as defined by CMS (2020) "is the unimpeded movement of species and the flow of natural processes that sustain life on Earth". Connectivity is essential for supporting species' movement for individual survival, mating, searching food and other resources, gene flow in metapopulations and for colonisation of new areas.

However, ongoing habitat fragmentation and loss continue to threaten such functions and cause decline of populations and even local extinction (Crooks et al. 2017; Westekemper et al. 2021). Wide-ranging species, such as large carnivores, are more likely to experience negative population-level effects of habitat fragmentation and to exhibit low tolerance for human activity (McClure et al. 2017).

The case of the Carpathian Mountains shows the importance of maintaining landscape connectivity on an international scale.

The ecological corridors keep landscapes permeable and one way to identify them is by the species-specific needs and the movement function they provide. Large carnivores naturally do not respect state boundaries or any other administrative or political frontiers; however, infrastructure and urban development is driven mainly by national strategies. The most efficient tool for maintaining landscape connectivity is the development and protection of ecological networks. In the case of the Carpathians, a robust supranational system of core areas and corridors is the proper solution.

Several projects and studies focused on identifying ecological networks and corridors in the Carpathians for large mammals, for example, the "Mapping conservation areas for carnivores in the Carpathian Mountains" (Salvatori 2004), "Potential habitat connectivity of the European bison (*Bison bonasus* L.) in the Carpathians" (Kuemmerle et al. 2011), "Identification and assessment of the potential movement routes for European bison in the North-East of Romania" (Deju 2011), "Creation of ecological corridors in Ukraine" (Deodatus et al. 2013), BioREGIO Carpathians project (Appleton and Meyer 2014) and Life Connect Carpathians (FFI 2019). No matter the selected focus species, the identification of ecological corridors used different methodologies, making the results non-comparable at the Carpathian level, sometimes not even at the national levels.

Our approach to identify the ecological network for large carnivores in the Carpathians (Papp et al., in prep.) (Fig. 4), was based on the habitat suitability models using the actual occurrence data of large carnivores (bear, wolf and lynx) and a set of environmental variables including abiotic, habitat and anthropogenic factors. According to the habitat suitability models, core areas and stepping stones were identified and their function in the Carpathians was discussed with local and national experts. At the same time, the resistance surface was derived from the habitat suitability model and fragmentation geometry was prepared in order to express landscape permeability for large carnivores. Finally, a connectivity model was prepared presenting a coherent network of core areas, stepping stones and corridors. This output was reviewed with experts and improved, based on their feedback in order to produce the final version of the pan-Carpathian ecological network. This is the first comprehensive ecological network projected at the Carpathian ecoregion level, offering a robust instrument for spatial planners and other stakeholders to identify from the early stages of planning different LTI or other large infrastructure projects, potential conflicts between economic projects and nature conservation. The intersection points between these two can be further explored and solutions tailored to allow both development and conservation.

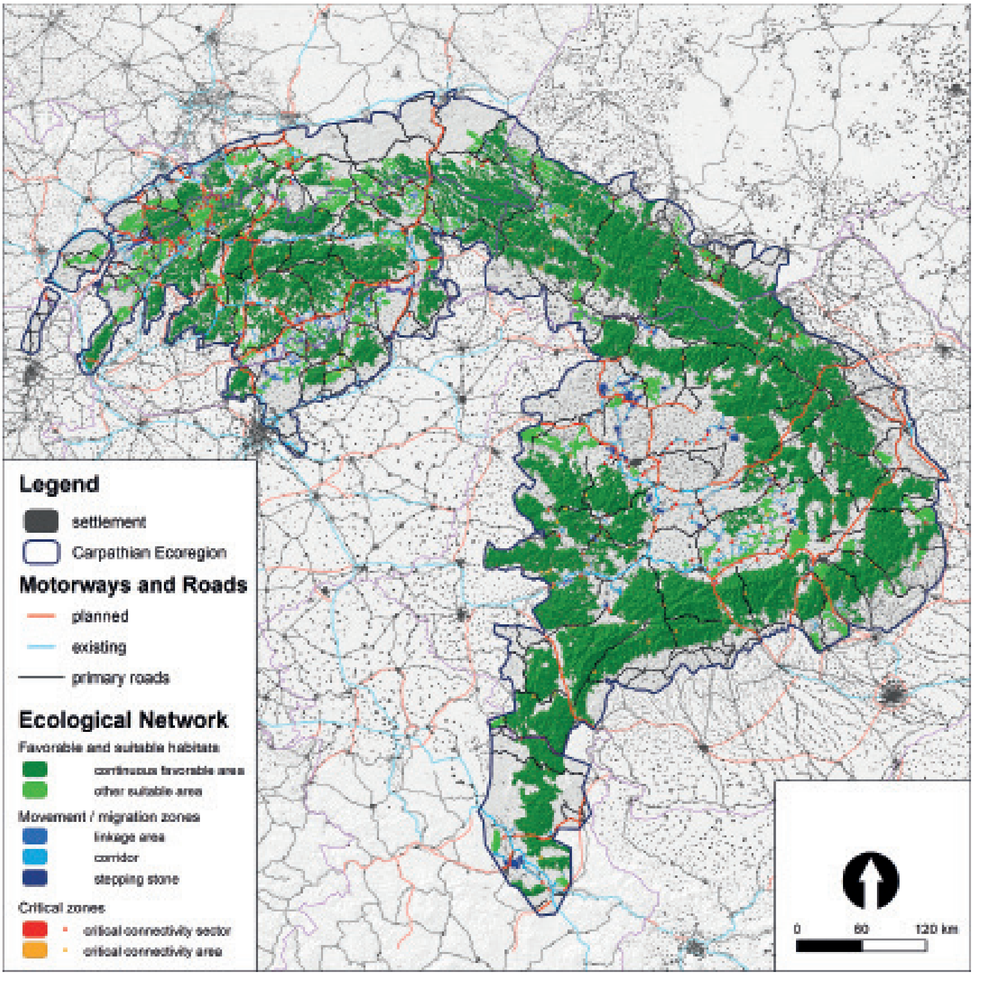

Figure 4. The ecological network for large carnivores in the Carpathians and the overlap with the transport network.

Other threats to ecological connectivity (beside transport) in the Carpathians

Another significant factor, which negatively influences ecological connectivity in the Carpathians, is increasing urbanisation and industrial development. The increasing human disturbance, especially around large cities and/or touristically attractive places, can also negatively influence wildlife, as well as natural habitats. This includes the use of 4×4 vehicles, jogging, biking and hiking, harvesting of non-timber products, hunting, skiing, the operation of ski lifts in the middle of protected areas etc.

Moreover, as a result of increasing intensive agriculture and large-scale forestry in many Carpathian countries, continuous and systematic loss of valuable large carnivore habitats is taking place.

The use of electric fences to prevent human-wildlife conflicts (e.g. to guard livestock, beehives, crops, orchards or properties, in general), although in principle an important and widely recommended conservation tool, can create a serious barrier effect, especially if deployed on a large scale.

The edge effect sometimes could possibly cause increased predation, increased mortality within corridors and the spread of invasive species and diseases. Some investigations confirm it to varying degrees (Haddad et al. 2015).

Last, but not least, climate change is also posing a serious, but hard to quantify threat at the moment to the Carpathian habitats.

Effects of current road and rail transportation on ecological corridors in the Carpathians

Transport development in the Carpathian region has been considerably delayed compared to western European countries. Accelerating the construction of motorways, trans-European roads and railways have brought accession to the EU to most countries (2004 - Czech Republic, Slovakia, Poland, Hungary; 2007 - Romania).

The Carpathians were inhabited by large carnivores continuously several decades ago. Bears, wolves and lynxes could move within mountain complexes with no limits. At that time, there was no need to delimit ecological corridors, because the area was continuously passable. The absence of officially designated ecological corridors and pressure to accelerate construction of transport infrastructure, or of other types of infrastructure, often led to the original ecological corridors being irreversibly interrupted.

Transport infrastructure in the Carpathians is typically located in mountain valleys as already indicated. Constructing new transport infrastructure in such areas always brings expansion of housing development as well. As a result, barriers often accumulate at the bottom of the valley - artificially fortified rivers, roads, motorways and railways - all run here in parallel and supplemented by residential and industrial development. Mountain valleys are, therefore, gradually becoming total barriers for animals. Some mountain complexes within the Carpathians are already surrounded on all sides by such barriers. Originally contiguous pan-Carpathian populations of large carnivores are gradually divided into smaller isolated units hardly capable of long-term survival. Transport infrastructure also involves animal mortality caused by traffic.

The level of fragmentation caused by transport infrastructure (Fig. 4) is, of course, different in various parts of the Carpathians. The western Carpathians along the border of the Czech Republic, Slovakia and Poland belong to the most affected parts. Rapid road and motorway development took place in this area during the past years and mountain ranges, such as Beskydy, Kysuce, Malá Fatra or Beskid Śląski, are almost isolated with a few last passages existing here, often only several tens of metres wide. The issue of fragmentation has already been given a lot of attention in this area for many years. All potential ecological corridors have been identified here and construction of several green bridges over existing roads and motorways is proposed at the most significant places. The situation is serious in other parts of Slovakia as well, but the solution is unfortunately complicated by the fact that a network of ecological corridors for large carnivores is not officially delimited here (Hlaváč et al. 2019).

Transport infrastructure development in Ukraine is, so far, not as fast as in other parts of the Carpathians. However, even here, quick recreational development occurs near existing roads, which creates barriers often tens of kilometres long.

Hungary is not a key country in terms of large carnivore occurrence and movement, but there are several areas in the north near the border to Slovakia (Bükk National Park or Aggtelek National Park), where a migration connection to Slovak populations still exists. In order to ensure the long-term existence of large carnivores in this area, it is necessary to identify and designate all significant ecological corridors and to manage them effectively, especially in places of their crossings with transport infrastructure and with the cross-border links to the Slovak populations that must be carefully taken into account.

Romania has the largest unfragmented forest areas and the largest populations of all three large carnivore species (Chapron et al. 2014). Due to the lack of official designation and recognition of ecological corridors in Romania, the effect of road and rail transportation on wildlife corridors has not yet been properly addressed. The current road network intersects several Natura 2000 sites. The first "green bridge" ever to facilitate the crossings of a highway (Lugoj-Deva) by large carnivores (Fig. 5F) was recently built (2018).

Ecological corridors have not been comprehensively defined in Serbia. There are also no studies trying to define the effect of current transport infrastructure on large carnivore populations in this country.

From the Carpathian countries, only the Czech Republic has officially delimited a network of ecological corridors for large carnivores. Delimiting ecological corridors and ensuring their protection in spatial planning remains a challenge for all Carpathian countries in the upcoming period. Whether the Carpathians can keep hosting viable populations of large carnivores in the future will depend on how well this challenge will be handled.

Positive and negative examples of transport infrastructure development in the Carpathians

Positive examples of transport infrastructure development in the Carpathians

During the railway reconstruction in the Beskydy Protected Landscape Area, eastern Czech Republic, two underpasses (Fig. 5A) were built. They meet the requirements to facilitate the movement of large carnivores. The permeability of the railway sections was improved, a fact that was confirmed by the sand belt monitoring and snow tracking of animals passing through the underpasses. Four ecoducts are currently under construction as part of the extensive modernisation of the D1 motorway between Prague and Brno as a contribution to defragmentation.

Figure 5. Positive examples of transport infrastructure development in the Carpathian countries **A** underpass constructed on the railway in the cadastre of the Mosty u Jablunkova close to national border in Czech Republic **B** overpass connecting the High and Low Tatra Mountains in Slovakia **C** overpass on M43 between Szeged and Nagylak in Hungary **D** blue retro reflectors installed on odometers on Main Road1 in Hungary **E, F** the first green bridge ever built in Romania on Lugoj-Deva highway, close to Brănișca Village

Besides some prolonged viaducts on some road sections, two green bridges exist in Slovakia. The first is connecting the High and Low Tatra Mountains (Fig. 5B). The second one is the so-called ACC (Alps-Carpathians Corridor) north of Bratislava that should enhance wildlife movements between Slovakia and Austria. This contribution to defragmentation started in 2016, being the first attempt in Central and Eastern Europe to build such a structure over an existing operating motorway.

Along the TEN-T network in Poland, several overpasses (green bridge-type crossings) that allow wildlife movement already exist. Moreover, bridges over watercourses are adapted to the migration/movement of animals. On the motorways, there are also structures for medium size animals, such as underpasses or culverts.

In Hungary, best practices refer to wildlife overpasses built over, for example, motorway M43 in south-east (Fig. 5C) or motorway M85 in the western part. Furthermore, several underpasses for medium-size animals, as well as noise, light-pollution and bird protection walls, have been built. Blue retro reflectors were also installed on odometers on Main Road1 in Hungary to reduce wildlife collisions (Fig. 5D).

As of today, there are no concrete examples of sustainable transport development in Ukraine, but there are intentions in this respect. Some decisions from the past can be considered as being sustainable, taking into account that they create conditions for permeability of motorways and railroads. They refer to the large bridges over Latorytsya River and the Beskydskiy Tunnel in the Carpathians, as well as numerous railroad culverts and bridges.

The first major transport infrastructure project in Romania that incorporated mitigation measures for ensuring connectivity within the landscape is the Lugoj-Deva highway. The original technical project was improved to include a system of solutions (i.e. tunnels, viaducts, green bridges) that allow the movement and dispersal of large carnivore species. Three green bridges have been built in total (Fig. 5E, F), two tunnels and three viaducts are expected to be realised according to the environmental permit.

There are no notable best practice examples in Serbia. At the moment, several highways are in the planning and designing process and possibilities/obligations for the construction of the migration/movement structures are explored; however, there is a perpetual problem of non-existing hard evidence of the ecological corridors at Serbian national level.

Negative examples of transport infrastructure development in the Carpathians

There are obviously many negative examples concerning the infrastructure development in the Carpathian region, even if they are not highlighted or properly documented.

For example, in the Czech Republic, the construction of four ecoducts in the southern and two that were built on the northern road circuit of Prague are very questionable. This is a suburban, very intensively used area, with high human activity. No endangered species can be expected to inhabit here or disperse through the road, which had a negative impression on public opinion about spending money on green bridges.

Zvolen–Kriváň section on R2 is a negative example from Slovakia. The express road has dramatic negative impacts on the movement of wildlife due to the absence of functional wildlife crossing structures. The road section completely isolates the valuable Poľana Mountain range, hosting the three large carnivore species, from the south of the country and further from Hungary.

The number, density and design of animal crossings is not optimal in Poland, not even in protected areas. The functionality of most passages for large and medium size animals is significantly limited by the structures' poor management/maintenance or use of the surrounding areas by humans. One example is the viaduct for large mammals close to Nietoperek, where the inappropriate height is limiting the possibilities of the animals to move from one way to another.

Hungary has a relatively low number of wildlife passages (40 in total, as of 2010) and they are not evenly distributed with regards to the main identified wildlife corridors. Hungary's largest viaduct is at Kőröshegy on the M7 motorway to the south of Lake Balaton. The necessity of this large viaduct was a topic of many debates at the end of the construction in 2007. In the proximity of the viaduct, a wildlife overpass was built in the correct location (leading out from a forest into a dirt road), but in a wrong way. It is basically not functional due to some technical mistakes/details that were overlooked. The monitoring of wildlife tracks revealed that deer and other species turned around.

In Ukraine, there are no dedicated wildlife crossings constructed at the moment and, generally, the movement needs of large mammals were not considered when LTI was developed.

Romania is another negative example where, due to the lack of an integrated approach in the case of Lugoj-Deva highway, a green bridge built in Brănișca area over the highway does not mitigate the negative effects of the adjacent existing county road and ends in the county road instead of passing it and leading the animals to the existing forest patch that borders the road.

In Serbia, there is a general belief amongst conservation groups that the development of LTI is done in a negative way, since the movement needs of animals are not properly addressed, partly because of the lack of ecological corridors designation and recognition. No dedicated wildlife structures have been built yet in Serbia.

Gaps in avoiding fragmentation by transport infrastructure development

We identified several gaps in terms of LTI development and connectivity conservation in the Carpathian ecoregion.

First of all, there are huge gaps in terms of knowledge availability, but also expertise and experience in properly dealing with the mitigation of negative effects of LTI. For countries like Romania, Serbia and Ukraine, this type of mitigation is relatively new and there is no sufficient national level capacity, expertise and experience to properly address and develop mitigation measures.

There are gaps in terms of understanding the effects and impacts of LTI projects in general. This is partly due to the fact that, generally, no studies have been carried out to assess the effects of LTI on wildlife and its movements or the effectiveness of the various mitigation measures, if any. In addition, the calculation and evaluation of cumulative effects is generally done in a very superficial way, in some ways because of the lack of clear criteria and guidance for evaluators and low public interest and participation in the spatial planning processes.

There is a lack of cooperation and open dialogue between many actors involved in the development of grey and green infrastructure. Usually, there is no genuine culture of cooperation between institutions in the countries of the region (this is still an effect of the former communist regime). This is a great barrier which should be overcome for the benefit and safety of both humans and animals.

There are also considerable practice gaps. There is no standard monitoring of the effectiveness of the implemented mitigation measures and already-built objects. There is no clear and documented evidence to understand or recommendations made about what types of mitigation measures work where and in which contexts. This type of monitoring is standard in many other countries and is perceived as a necessary step towards increasing the efficiency of funds spent to ensure the permeability of LTI for animals.

There is also a lack of studies on migration/movement behaviour of large carnivores in the Carpathian ecoregion. There are no harmonised methodologies implemented to perform large carnivores monitoring, sometimes not even at national levels (e.g. in Romania and Ukraine). Some studies were performed, especially in protected areas; however, that is not enough to avoid landscape fragmentation for large carnivores.

Generic biodiversity-related data are available at the EU level through different databases developed by the European Commission and the EEA. However, there are significant differences between the national databases. In some countries, data are typically scarce, especially in Romania, Ukraine and Serbia. In Romania, for instance, there is no national biodiversity database publicly available, which might help in identifying potential conflicts with transport infrastructure development in biodiversity-rich areas as in protected areas.

Open information on spatial distribution of roads and railways and their categories is commonly available from infrastructure managers for all countries, but not necessarily in GIS shape format. There is also a lack of official open spatial data. A good alternative is the OpenStreetMap project, which of course does not provide detailed or technical information such as, for example, green infrastructure elements.

Traffic intensities on roads are usually collected once in five years through detailed traffic censuses to the level of regional roads. Full data in spatial form are not freely available on-line in any country. Some countries present them in a map form in their respective viewer application or as exported raster maps (Czech Republic, Slovakia, Poland, Hungary). For Romania, detailed data are available from CESTRIN137 only as a paid service.

A source of traffic intensities is UNECE's e-Roads census, which only covers major roads included in the European Agreement on Main International Traffic Arteries "AGR". There is no intensity data for road traffic in Ukraine at all.

No data were collected within our projects regarding the level of disturbances from traffic. Information on these effects is generally missing; however, partial information on noise pollution can be obtained from the mapping done by the EU member states to assess exposure to noise from key transport and industrial sources and made available through two initial reporting phases, 2007 and 2012. This was required by the

Environmental Noise Directive (European Commission 2002). This mapping should also cover (besides the other sources) roads with annual traffic exceeding 3 million vehicles. In some countries, such data are available as raster in internet-based viewer applications and not as shape files.

Information about wildlife mortality on roads is quite well collected in Czech Republic from various sources, such as Nature Conservation Agency, police accident database, hunters; a common database is available for viewing on the webpage of the Transport Research Centre. Other countries (Ukraine, Poland) collect roadkill information through police, but Ukrainian data cannot be analysed properly due to the fact that the registration includes both domestic and wild animals. Romania started to implement a similar roadkill application tool as the one from Czech Republic, but not in a coordinated way at the national level. For Serbia, this type of information is not available.

Conclusions

The Carpathians are home to many large mammal species, including the three large carnivore species: brown bear, grey wolf and Eurasian lynx. The LTI network is not fully developed in the area, which gives the countries of the region the chance to plan and implement proper mitigation measures in adequate places to allow wildlife movement across the landscape. Mitigating for LTI at the regional level of the Carpathians will prevent habitat fragmentation and maintain the viability of large mammal populations and their associated ecosystems.

The issue of wildlife movement and transport has been generally underestimated in the ecoregion, so far. Only a few studies on the impact of traffic on wildlife movement and behaviour have been carried out. We emphasise the role and importance of performing high quality studies and recommend them especially in countries where the level of knowledge and experience in reducing the impact of LTI on ecological connectivity and wildlife is low.

The harmonisation of grey and green infrastructure is a long-term and complex process, but essential for both human safety on roads and well-being of large carnivores. Inclusive stakeholder participation, including improved communication, knowledge, data sharing and regular exchange and cooperation between Environmental, Transport and Spatial planning sectors, as well as other relevant parties, within the framework of, for example, stakeholder platforms, is needed from the early planning processes. Moreover, we recommend sustained cooperation with international professional bodies and networks (e.g. IENE - Infra Eco Network Europe) especially in countries with no or low experience and expertise in addressing the need for developing and implementing the most appropriate mitigation measures in the case of new LTI or upgrading process. Besides, other positive and negative examples of LTI development from around the globe should be made widely available especially to road and railway development and construction companies, decision-makers and other key stakeholders.

In terms of legislation related to the protection and implementation of ecological corridors, there are differences in the Carpathian region between the EU and non-EU countries, western and eastern countries and, in general, between countries. In principle, all Carpathian countries have legislation in place for ecological connectivity, but in practice and implementation, there are gaps and discrepancies due to either lack of harmonised legislation across relevant sectors, enforcement, funding or available tools (e.g. absence of the methodology for the official designation of ecological corridors). We recommend to improve and harmonise the legislation related to ecological connectivity and sustainable transport development in the Carpathian countries.

We suggest that the development and endorsement of methodologies for the official designation of ecological corridors in the Carpathian countries should be accelerated to avoid the interruption of ecological connectivity, especially in sensitive areas.

The assessment of cumulative impacts is superficially addressed in the Carpathian ecoregion. We stress the need that the planning and development of LTI, as well as mitigation measures, should also consider other potential barriers and threats to large carnivores at landscape level. In this respect, we also recommend that a transdisciplinary approach to the conservation of large carnivores should be widely applied in the Carpathians to decrease the threats to this group of species, as well as to ensure their sustainable conservation.

We urge the development of national and regional transparent databases where they are absent, including with roadkill information to facilitate the identification of conflicts with large carnivores and the selection of proper mitigation measures and locations where they should be implemented.

Monitoring of both wildlife and transport, including the efficiency of different wildlife crossing types in different contexts, is important to understand and justify the measures that are required for a sustainable transport network in the Carpathians and beyond.

A pool of experts and professionals should be developed in all sustainable transport-related fields. Road ecology needs more attention and development in the Carpathians.

Transboundary and transnational cooperation on improving ecological connectivity and conserving large carnivores is needed for a greater impact and coordination of efforts.

The effects of climate change on large carnivores and their habitats are not closely monitored in the Carpathians. The species' distribution and the location of ecological corridors might change due to habitat transformation and shifts. It is important to closely monitor and observe, respectively, to understand the changes and impacts of future climate changes on large carnivores and ecological corridors so that targeted actions can be identified and implemented in response. This is particularly important since ecological corridors are identified, based on the current distribution of habitats and focal species. However, we also have to consider the projections of the future distribution and changes in terms of habitats. Ideally, ecological networks should incorporate the connectivity needs of both current and future habitats. The same should be considered for any mitigation measures defined, to respond to both the present and predicted future needs of wildlife and society.

Our recommendations can also easily be implemented in other countries and mountain regions of the world, where there are similar main problems: increasing pressures and threats from LTI development on rich biodiversity areas and lack of harmonisation between the green and grey infrastructure. In such regions, the available knowledge and expertise is generally scarce and mistakes can be irreversible without proper documentation and guidance. In addition, improved connectivity between adjacent mountain ranges is crucial, especially when talking about species with large space requirements and in the light of the current global changes.

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