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EFFECTS OF INFRASTRUCTURE DEVELOPMENT ON LARGE CARNIVORES

An European review of impact evaluation and mitigation procedures

VOLUME 1

Dissertação no âmbito do mestrado em Ecologia orientada pelo Professor Doutor Francisco Álvares e pelo Professor Doutor Paulo Gama Mota e apresentada ao Departamento de Ciências da Vida da Faculdade de Ciências e Tecnologia da Universidade de Coimbra.

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Resumo

Com o crescimento da população humana vem também a expansão da urbanização, aumento da exploração de recursos e, consequentemente, o aumento das perturbações à vida selvagem. Grandes carnívoros, tendo vastos territórios, são particularmente propensos a sofrer impactos negativos dessas perturbações. Como tal, foi realizada uma revisão da literatura relativa aos efeitos e mitigação de infraestruturas antropogénicas em grandes carnívoros, com foco nas seis espécies que existem atualmente na Europa; lobo cinzento, urso pardo, lince eurasiático, lince ibérico, glutão e chacal dourado. Parte dessa revisão concentrou-se em publicações científicas e programas de conservação na Europa e, adicionalmente, também foi realizada uma revisão referente à América do Norte, por motivos de comparação. Por fim, um questionário online sobre processos de avaliação e mitigação de impactos foi enviado para especialistas em grandes carnívoros. Foram analisados quais os parâmetros biológicos afetados e o tipo de resposta para os diferentes casos, bem como o tipo de medidas de mitigação propostas. A revisão revelou uma maior quantidade de informação relativa ao lobo cinzento e ao urso pardo em comparação com as restantes espécies em estudo, assim como a existência de um maior foco em estradas e áreas urbanas do que em outros tipos de infraestruturas. Contudo, foi demonstrado que os grandes carnívoros, em geral, são afetados negativamente por vários tipos de infraestruturas. A análise estatística com recurso a GLM e análise de clusters mostrou que o número de publicações por país estava relacionado ao status de proteção das espécies de grandes carnívoros e à densidade da rede rodoviária, a nível nacional. O estatuto de proteção da espécie também esteve relacionado com o número de publicações que mencionam medidas de mitigação. A revisão da literatura, juntamente com o inquérito online, destacou a necessidade de mais foco na avaliação de impactos e medidas de mitigação.

Palavras-chave: grandes carnívoros, infraestruturas, impactos, medidas de mitigação, Europa

Abstract

Along with human population growth comes urbanization expansion, higher resource exploration and, consequently, increased disturbances to wildlife. Large carnivores, having large home ranges, are particularly prone to suffer negative impacts from these disturbances. As such, a literature review was conducted pertaining to anthropogenic infrastructures effects and mitigation on large carnivores, focusing in the six species currently occurring in Europe; grey wolf, brown bear, Eurasian lynx, Iberian lynx, wolverine and golden jackal. Part of this review was concentrated scientific publications and conservation programs in Europe and, additionally, a review pertaining to North America was also conducted, for comparison purposes. Finally, an online questionnaire regarding impact evaluation and mitigation was sent to large carnivore experts. Affected biological parameters and type of response were analyzed for the different cases, as well as the type of mitigation measures proposed. The review showed that there is more information on grey wolves and brown bears compared to the other target species, as well as a larger focus on roads and urban areas than on other infrastructure types. Regardless, large carnivores in general were demonstrated to be negatively affected by various types of infrastructures. Statistical analysis, using GLM and cluster analysis, showed that the number of publications per country was related to large carnivore species' protection status and road network density, at a national level. The species' protection status was also related with the number of publications mentioning mitigation measures. The literature review, along with the online survey, highlighted the need for more focus on impact evaluation as well as on mitigation measures.

Keywords: large carnivores, infrastructures, impacts, mitigation measures, Europe

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1. Introduction

Human population has been on a steady rise, going from an estimated 2,5 billion people in the 1950's to reaching a total of 8 billion in 2022 (United Nations, 2022). With such a population growth comes an increased human need for space and resources, which, in turn, results in the disturbance, fragmentation and destruction of natural habitats, bringing several consequences for biodiversity (Liu et al., 2016). These anthropogenic changes impact entire wildlife communities, forcing animals to adapt their normal behavior to face unfavorable circumstances, as different species may lose access to their main food sources, refuges or denning sites or even become isolated from their conspecifics by physical barriers (Templeton et al., 1990; Arroyo-Rodríguez & Dias, 2010). Consequently, as a result of this conversion of natural habitats into areas designed to accommodate anthropogenic needs (such as infrastructures, industrial production or recreational activities), numerous animals and plants are facing extinction, either locally or globally (Chiang, 2007; Crooks et al., 2017). A diverse array of studies has been conducted throughout the years to analyze the effects of human activity and infrastructures on various types of living organisms, with most being focused on linear transport infrastructure, particularly roads (e.g. Spellerberg, 1998; Trombulak & Frissell, 2000; Fahrig & Rytwinski, 2009) and urban areas as a whole (e.g. (Ditchkoff et al., 2006; McKinney, 2008). Due to the increasing expansion of road networks and urban facilities, it should be kept in mind that any anthropogenic modification on natural habitats is going to possibly constitute a new challenge to biodiversity. Besides, development of human activities is associated to several other infrastructures that can potentially impact wildlife in several ways. Fences, power lines, windfarms, touristic facilities and open mine pits are some examples of understudied infrastructures warranting more attention to how wildlife interacts with them (Ferrão da Costa et al., 2018). Furthermore, it's of extreme importance that the impacts of human-build infrastructures on biodiversity are properly studied and evaluated, in order to efficiently avoid or, at least, minimize the negative effects as much as possible (Papp et al., 2022). This need is especially relevant in human dominated landscapes such as the European continent, and for wide ranging species sensitive to human disturbance, such as large carnivores.

1.1. Ecological traits of European large carnivores

Large carnivore are large-sized mammals (>15 kg) that require meat on their diet, even if they consume other types of food, such as plants and fruits (Ripple et al., 2014). These species typically have wide movement patterns and, therefore, require large home ranges (May et al., 2006). Besides, these are species with low reproductive rates, meaning their offspring are usually few and far between, as they take a relatively long time to fully develop (Cardillo et al., 2004). These characteristics make large carnivores particularly vulnerable to habitat modifications promoted by humans (Macdonald et al., 2022).

On the other hand, large carnivores also have negative impacts on humans, such as predation on livestock (van Eeden et al., 2018). Livestock are generally easy targets for large carnivores and in areas where wild prey densities are comparably lower, large carnivores are likely to take advantage of anthropogenic food resource (Kumaraguru et al., 2011). This results in financial losses for the livestock producers and, consequently, in the escalation of human-wildlife conflicts. Attacks on people, pets and destruction of beehives also contribute to perpetrate conflict and retaliatory actions, which usually include direct persecution and poaching towards carnivores (Moreto, 2019).

Nevertheless, large carnivores actually play an important role in maintaining ecosystem health and resilience by applying a top-down control (Hoeks et al., 2020), which is when species from higher trophic levels exert regulation on lower trophic level species by preying on the latter. This helps prevent overgrazing by herbivores and its associated consequences on the entire ecosystem (Beschta & Ripple, 2016). Large carnivores are also considered “umbrella species” (Steenweg et al., 2023), i.e. a species, usually with large home-ranges, whose preservation is expected to produce positive results on the conservation of several other co-occurring species. This concept has been used to counter adversities in conservation such as limited funding, knowledge and time for action (Roberge & Angelstam, 2004).

Taking all of this into consideration, understanding the impact that human modifications have on large carnivores should be seen as a relevant topic for achieving an effective conservation of wildlife as well as a more ecologically friendly landscape planning, which is especially relevant in the European continent.

Europe is a relatively small region (10,53 million km^2) with a high degree of urbanization and high human population density (average of 34 inhabtitants/km^2) where there is a clear lack of large natural areas untouched by humans. Therefore, wildlife conservation models in Europe are typically based on land-sharing (presence of wildlife on agricultural land) rather than the land-sparing approach (separation of land for wildlife conservation from human-modified land) employed in other continents such as north America and Africa, where large carnivores are mostly confined to wide protected areas, often fenced and without human interventions (Stephens, 2015; Karner et al., 2019). As such, in the land-sharing approach common in Europe, a closer proximity between humans and large carnivores is inevitable, implying mutual consequences on both sides, which is main reason why the topic related to infrastructure development is so relevant.

In Europe, there are 6 species of large carnivores: grey wolf (*Canis lupus*), brown bear (*Ursus arctos*), Eurasian lynx (*Lynx lynx*), Iberian lynx *(Lynx pardinus*), wolverine (*Gulo gulo*) and golden jackal (*Canis aureus*).

The grey wolf is the largest extant member of the Canidae family and it's native to Eurasia and North America (Figure 1; Table 1). In Europe, the largest populations are located in the Carpathians, Dinaric-Balkans, Baltic countries and in the Italian peninsula. In the Central European lowlands (Germany, Poland) there's also a stable population. On the other hand, the Scandinavian, Karelian, Alpines and Northwestern Iberian subpopulations are considerably smaller and at higher risk (Figure 1). The wolf is a highly social species, mostly living in territorial packs (usually composed by a breeding pair and their offspring) specialized in cooperative hunting (Geptner et al., 1988), although some dispersing individuals are solitaire. The wolf typically shows preference for habitats with higher forest cover such as woodlands, although It can also occur in open habitats and agricultural areas (Jędrzejewski et al., 2004, 2005). This species worldwide is not currently facing extinction but, as was stated above, there are some isolated populations that are considered threatened (e.g. Portuguese South Douro and Scandinavian subpopulations). In spite of the vicious reputation that classical tales have helped promoting, wolf attacks on humans are actually quite rare although its predation on livestock is at the forefront of several conflicts with humans. In fact, the persecution of wolves resulting from these conflict has made human caused mortality one of the most important threats to the species (Salvatori & Linnell, 2005). Other threats to wolf conservation are habitat fragmentation and disturbance, which is related to decreasing available areas to establish territories and reproduce due to urban expansion and infrastructure development (Eggermann, 2009).

Figure 1: Grey wolves (left); Grey wolf distribution in Europe from 2006-2011, with reference to subpopulations (in blue). Dark cells indicate permanent occurrence; grey cells indicate sporadic occurrence (right). (source: Kaczensky et al., 2013)

Table 1: General information on *Canis lupus*

Grey Wolf (*Canis lupus*)	
Body mass	20-60kg in males, 15-55kg in females
Home range	100-1000km^2
Mating season	January-March
Gestation period	+/- 2 months
Litter size	1-11
Diet	wild ungulates, small and medium-sized vertebrates, livestock, invertebrates, fruits, vegetables, carrion and human-related garbage
IUCN Red List status	Least Concern

The brown bear is the second largest terrestrial carnivore in the world (Figure 2; Table 2), only behind the slightly larger polar bear (*Ursus maritimus*) (Hunter, 2020). Brown bears can be found in Eurasia and North America, with the largest European subpopulations being located in the Carpathian, Dinaric-Pindos, Scandinavian and Karelian regions, while there smaller but apparently stable subpopulations occur in the Cantabrian, Baltic and Eastern Balkans' regions (Figure 2). On the other hand, the Alpine, Pyrenean and Apennine subpopulations are currently threatened and listed in the IUCN Red List as Critically Endangered (iucnredlist.org). Bears usually select forest habitats, mostly mature hardwood forest, and lower elevations (Clevenger et al., 1997). In contrast to wolves, brown bears are characteristically solitary animals, though there's evidence of an existing complex social structure between related females (Støen et al., 2006). During winter, bears enter into a state of torpor, lowering their heartbeat, circulation and breathing, just enough to still be able to easily wake up and defend their den at any time, unlike small mammals like marmots that go into full hibernation (Jensen & Fago, 2021). To survive during winter, bears need to increase their food intake during the leading months in order to store enough fat in their bodies, in what's called "hyperphagia period" (Coogan et al., 2018). The worldwide population of brown bears is not currently considered to be threatened, however, conflicts with humans are not uncommon, as their predation on livestock and beehives as well as the construction of infrastructure inside bear habitats generate negative interactions (Morales-González et al., 2020).

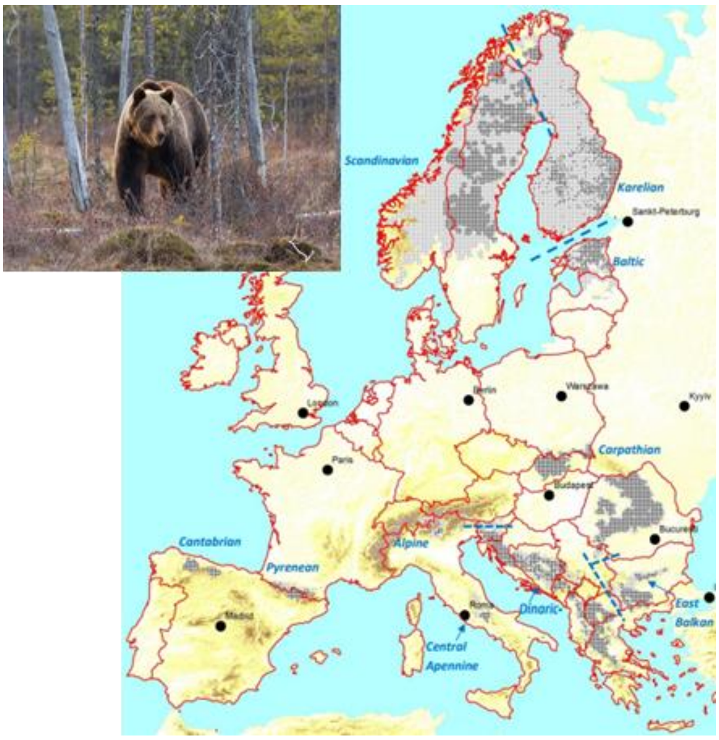

Figure 2: Brown bear (left); Brown bear distribution in Europe from 2006-2011, with reference to subpopulations (in blue). Dark cells indicate permanent occurrence; grey cells indicate sporadic occurrence (right). (source: Kaczensky et al., 2013)

Table 2: General information on *Ursus arctos*

Brown Bear (*Ursus arctos*)	
Body mass	140-320kg in males, 100-200kg in females
Home range	120-1600 km^2 for males, 60-300 km^2 for females
Mating season	May-July
Gestation period	6-9 months
Litter size	1-3 cubs
Diet	wild ungulates, small to medium-sized vertebrates, livestock, fish, invertebrates, honey, fruits, vegetables, roots, eggs, carrion and human garbage
IUCN Red List status	Least Concern

The Eurasian lynx occurs from Europe to central Asia and is currently the largest cat species native to Europe (Figure 3; Table 3). Like most felids, it has solitary habits, with most social interactions occurring during mating season and in the form of territorial fights (Mattisson et al., 2012). The Eurasian lynx population worldwide does not appear to be under serious threat, although some European subpopulations like the Bohemian-Bavarian-Austrian, Harz Mountains, Balkans and, especially, the Vosges Palatinian ones are facing high risk of extinction (lcie.org). The situation in the Alps, Jura Mountains and Dinaric areas is not as extreme but should still be under major surveillance. The largest populations in Europe can be found in Karelia, Carpathians, Scandinavia and in the Baltic countries (Figure 3). Eurasian lynx select areas with dense forest cover and rugged terrain (Bouyer et al, 2015). Infrastructure development contributes to the fragmentation of subpopulations, though the role of poaching and legal hunting (in countries such as in Norway and Romania) represent one of the biggest threats to this species in the European continent (Andrén et al., 2006).

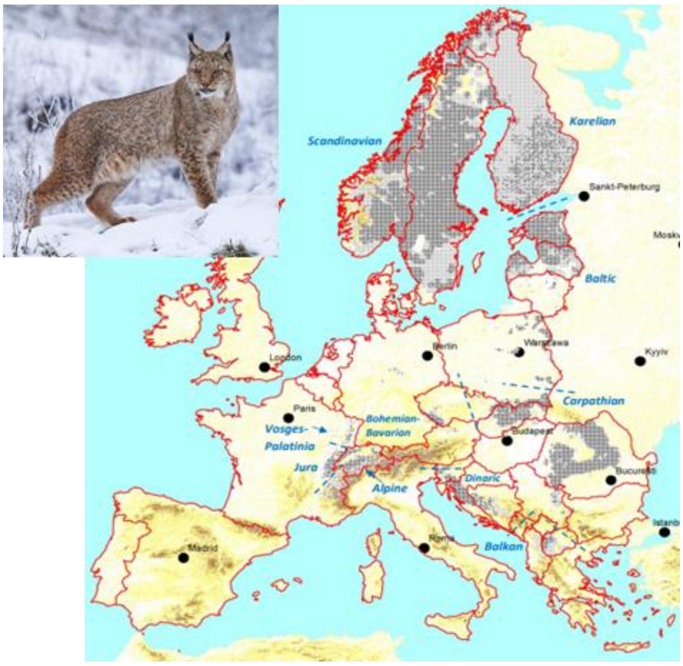

Figure 3: Eurasian lynx (left); Eurasian lynx distribution in Europe from 2006-2011, with reference to subpopulations (in blue). Dark cells indicate permanent occurrence; grey cells indicate sporadic occurrence (right). (source: Kaczensky et al. 2013)

Table 3: General information on *Lynx lynx*

Eurasian Lynx *(Lynx lynx*)	
Body mass	18-25kg in males, 12-16kg in females
Home range	120 to 1800 km^2 for males, 80 to 500 km^2 for females
Mating season	March
Gestation period	+/- 2 months
Litter size	1-4 cubs
Diet	wild ungulates, lagomorphs, rodents, mustelids and other small vertebrates, birds and livestock
IUCN Red List status	Least Concern

The Iberian lynx (Figure 4; Table 4) is endemic to the Iberian Peninsula (Figure 4), where it preferentially selects woodlands habitats with lower percentage of tree cover (Palomares, 2000; Gastón et al., 2016). It shows a trophic dependency on rabbits, which together with its as well as their solitary habits and human-induced impacts (such as roadkills, poaching and habitat modification) contributed to make this species one of the most endangered cat species in the world. Iberian lynx almost went extinct during the last century, especially due to human persecution and the spread of myxamatosis and viral hemorrhagic disease epidemics in the rabbit populations (Sarmento et al., 2011). Fortunately, due to the efforts of *in situ* and *ex situ* conservation actions, the species' population is now slightly recovering and considered more stable, although still under threat (Figueiredo et al., 2021).

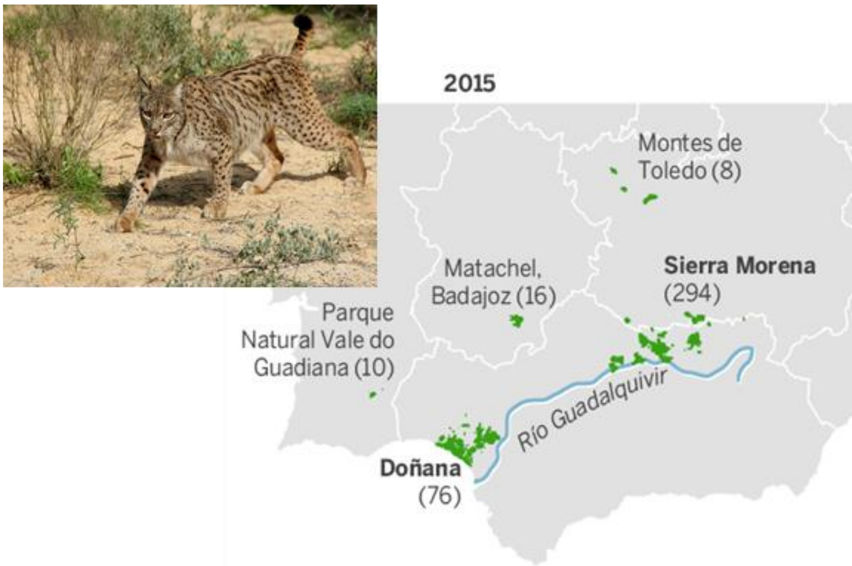

Figure 4: Iberian lynx (left); Iberian lynx distribution in 2015, with reference to permanent occurrence in green (right). (source: iberianature.com)

Table 4: General information on *Lynx pardinus*

Iberian Lynx (*Lynx pardinus*)	
Body mass	11-15kg in males, 8-12kg in females
Home range	10-17 km^2 for males, 5 to 12 km^2 for females
Mating season	January
Gestation period	+/- 2 months
Litter size	1-4 cubs
Diet	rabbits and other small vertebrates, birds, young wild ungulates and livestock
IUCN Red List status	Endangered

The wolverine is the largest land-dwelling member of the Mustelidae family (Pasitschniak-Arts & Lariviere, 1995) and can be found in North America and Eurasia (Figure 5; Table 5). In Europe, it is only present in the Fennoscandia Peninsula (Figure 5), divided in two subpopulations; the Scandinavian subpopulation is larger while the Karelian subpopulation is considerably smaller although appearing to be slowly increasing in recent years (lcie.org). Wolverines appear to select high alpine areas, which may include shrubland and tundra (May et al., 2006). Similar to the brown bear, the wolverine has delayed implantation, meaning the fertilized eggs remain in the blastocyst stage until late autumn-winter, under the possibility that females may not produce offspring if food and resources are scarce (Mead, 1989). Wolverines are primarily scavengers, however, European populations appear more prone to hunting than their North American conspecifics, likely because of the lower density of competing predators in Europe (1st International Symposium on Wolverine Research and Management). Overall, the wolverine is in a precarious conservation status in Europe, with illegal killing being one of the main threats along with habitat fragmentation (Rauset et al., 2016)

Figure 5: Wolverine (left); Wolverine distribution in Europe from 2006-2011, with reference to subpopulations (in blue). Dark cells indicate permanent occurrence; grey cells indicate sporadic occurrence (right). (source: Kaczensky et al., 2013)

Table 5: General information on *Gluto gluto*

Wolverine (*Gulo gulo*)	
Body mass	12-18kg in males, 8-13kg in females
Home range	100 to 500 km^2 for males, 100-200 km^2 for females
Mating season	June-August
Gestation period	1-1/2 months
Litter size	1-3 cubs
Diet	carrion, wild ungulates, small mammals and livestock
IUCN Red List status	Vulnerable

Finally, the golden jackal is a close relative of the grey wolf, although much smaller in size (Figure 6; Table 6). It is found in Europe and Asia, and has been expanding its distribution in the European continent over recent years, where it has subpopulations occurring in the Central and Southeastern regions (Figure 6). Golden jackals show a high habitat plasticity, with preference towards areas with shrub-herbaceous vegetation and even heterogeneous agricultural lands, however, it can easily adapt to different types of habitats (Šálek et al., 2014). Similarly to wolves, golden jackals are social canids, with territorial groups consisting of a breeding pair and their offspring (Macdonald, 1979). Golden jackals exhibit highly opportunistic behavior when it comes to food, feeding mainly on carrion and even human-related garbage (Geptner et al., 1988, Lange et al., 2021). This helps making it a very adaptable species, despite legal culling, illegal killing and roadkill being possibly the main threats to its survival (Männil & Ranc, 2022).

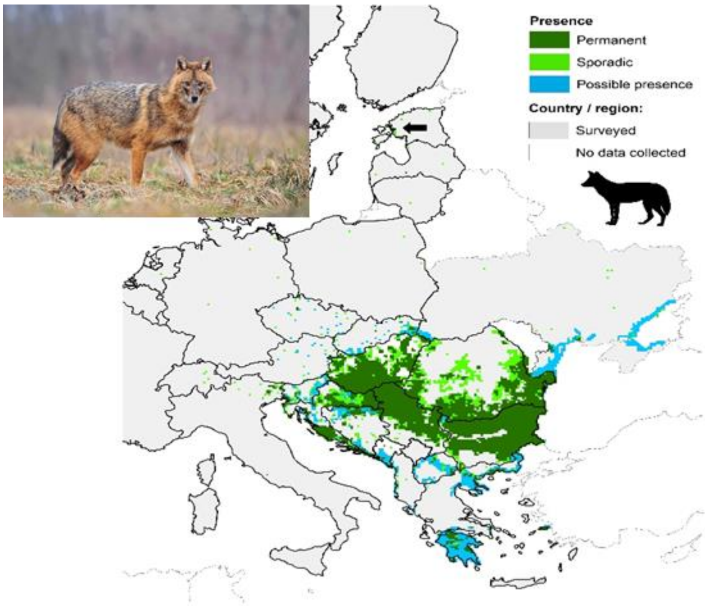

Figure 6: Golden Jackal (left); Golden jackal distribution in Europe, in 2018, with reference to permanent occurrence (dark green) and sporadic occurrence (light green) (right). (source: lcie.org)

Table 6: General information on *Canis aureus*

Golden Jackal (*Canis aureus*)	
Body mass	9-15kg in males, 8-12kg in females
Home range	8-15 km^2
Mating season	February-April
Gestation period	+/- 2 months
Litter size	1-4 cubs
Diet	carrion, small and medium-sized mammals, birds, reptiles, young livestock, human garbage, fruits and other plant based material
IUCN Red List status	Least Concern

1.2. Large Carnivores and infrastructure development

Infrastructure development keeps increasing with time, accompanying the human population growth. Urban areas (Figure 8) are expanding and, consequently, the need for viable travel routes connecting each urban area results in an increasingly higher linear transport infrastructure density, encompassing railways and road networks (Papp et al., 2022). Europe has a high road density (Figure 7), with values for motorway density surpassing 100 km per 1000 km^2 in cities like Budapest, Wien and Hamburg (Eurostat.eu).

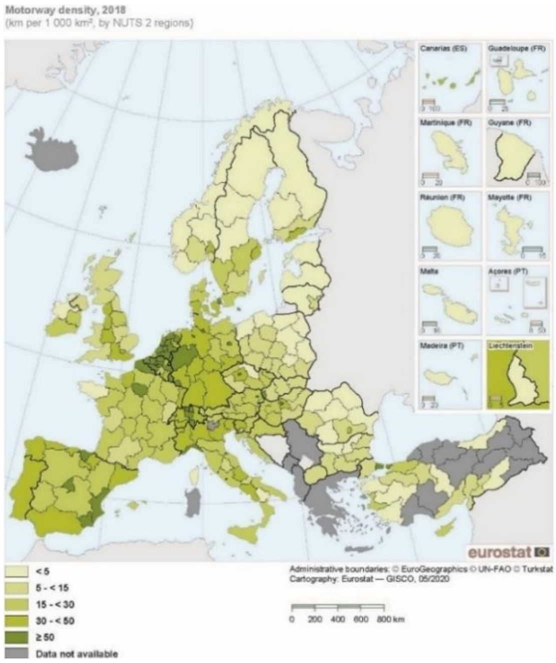

Figure 7: Motorway density in Europe, in 2018 (source: EUROSTAT)

There are different types of roads (Figure 8), including the larger highways featuring fast-paced traffic, main paved roads with comparably slower traffic, as secondary paved roads, with even less traffic, and forest roads (or unpaved roads) where there is much less disturbance and, in theory, a closer proximity to wildlife (Swenson et al., 1996; Thorsen et al., 2022). Additionally, the search for close contact with nature, in regards to tourism, has resulted in the development of resorts (such as ski resorts), recreational cabins and even viewpoints, which may all have potential effects that are currently disregarded, in general (Nellemann et al., 2007; Sahlén et al., 2011, Zarzo-Arias et al., 2018). Fences are another progressively common type of infrastructure, designed to enclose a certain area to prevent outside access. As such, fences can be employed to control border crossings, prevent spread of diseases or protect private property, which may include agricultural fields and livestock, leading to important barriers to the movement of large carnivores (Trouwborst et al., 2016; van Eeden et al., 2018).

Power lines (Figure 8) and pipelines, used to carry electrical power and liquids, respectively, are infrastructures that usually are not considered as possible disturbances to large carnivores, although negative effects can be associated with them, particularly during the construction period (Dickie et al., 2017).

Infrastructures related to renewable energy development have been on the rise for the last few years, as global warming and pollution lead to a search for eco-friendlier ways of generating energy, with less emission of greenhouse gases and less dependency on fossil fuels (Dincer, 2000). Consequently, wind farms (Figure 8), solar power plants and hydropower complexes have become more prevalent in the landscape, as renewable energy currently makes for around 20% of total energy consumption in Europe (Eurostat.eu). Nonetheless, these infrastructures are still human modifications and disturbances to the natural environment, and therefore may be associated with important effects on large carnivores, such as habitat fragmentation or disturbance (Ferrão da Costa et al., 2018; Delayat et al., 2019).

Even though an association could be established between infrastructure presence and human activity, implying it would be the latter that actually produced effects on large carnivores and other wildlife, negative consequences are not exclusive to infrastructures in use, as abandoned open-pit mines that were once used for mineral extraction may remain liable to impact wildlife (Cristescu et al., 2011).

Figure 8: Examples of some anthropogenic infrastrucutres: roads, urban areas, power lines and wind farms

All the aforementioned infrastructures can be associated with effects, either negative or positive, on the biological parameters of large carnivores. For instance, infrastructure development can influence occurrence (i.e. presence level) as well as habitat selection, – both for foraging sites and breeding/resting sites –, although it can either attract or exclude these animals (Bouyer et al., 2015). It can also affect their movement patterns, with unpaved forest roads or low-traffic paved roads being frequently used as travel corridors or foraging areas for many large carnivores (Dickie et al., 2017). However, on the contrary, crossing roads and railways, especially in areas of high traffic volume, can lead to high levels of roadkills or become dangerous enough to prevent individuals from even trying to cross them, resulting in isolated populations (Dennehy et al., 2021). Consequently, gene flow can also be affected as it becomes harder for these animals to find unrelated mates, which raises implications on genetic diversity (Fedorca et al., 2019). These negative effects on connectivity can also happen with long border fences, since these structures have the sole purpose of acting as a barrier (Trouwborst et al., 2016). Besides, in some border security fences there are cases of animals getting stuck and become severely injured or not be able to disentangle themselves before dehydrating (Linnell et al., 2016).

Crossing transport infrastructures is mainly associated with a high mortality risk due to traffic collisions, which is probably one of the most obvious consequences of infrastructures and among the most well-studied (Colino-Rabanal et al., 2011; Sidorovich et al., 2020). However, it's not only moving vehicles that can result in the direct mortality of large carnivores, since power lines, when damaged, can cause accidental electrocutions (Desmecht, 2017; Biasotto et al., 2021). Besides, the mere presence of large carnivores near anthropogenic infrastructures with human presence leaves them more prone to direct persecution or other causes of human-related mortality (Bunnefeld et al., 2006). Moreover, being in proximity to infrastructures and, as a consequence, to human activity can also trigger stress and other behavioral responses (e.g. changes on daily activity patterns) that differ from the animal's normal state (Clevenger et al., 1997). All these effects can, in their own way, affect survival, fitness or reproduction; if an animal has constraints finding mates, foraging sites or breeding areas, may lead to high levels of stress or reduced reproductive success (Eggermann, 2009).

Impacts of infrastructures on large carnivores can be either direct or indirect. Direct impacts are those when an individual is affected by the infrastructure itself, like a fence preventing connectivity or movements. Indirect impacts occur when the infrastructure itself doesn't appear to directly affect a large carnivore but may be associated with other consequences, such as higher mortality risk when near areas with human presence. There are also cumulative effects, related to the presence of several types of infrastructures in certain areas, that, when together, can intensify the potential impacts that would be expected by each infrastructure on its own (Eftestøl et al., 2021). To sum up, several infrastructures combined even a single infrastructure can affect large carnivores at many levels, either positively or negatively. In this context, the behavioral responses from large carnivores can be dependent on the infrastructure type, the regional context, the species' own characteristics and, most likely, on individual traits (May et al., 2008; Milanesi et al., 2022).

1.3. Evaluation and mitigation of infrastructure impacts on large carnivores

Given the known negative effects of infrastructures on large carnivores, it becomes crucial to rigorously address, evaluate and mitigate potential impacts of new constructions, although this is not exactly a simple task for several reasons. Large carnivores, despite their size and wide home ranges, are typically elusive animals that are difficult to study, especially in more remote areas. Main survey methods for wildlife, such as GPS and radio collars, camera-traps, acoustic stimulations and scat surveys (along with the analysis of other biological samples) are commonly employed to study the behavior of large carnivores (Giannatos et al., 2005; Ferrão da Costa et al., 2018; Sawaya et al., 2019). However, these techniques often provide few information or sample sizes for a proper impact evaluation, forcing researchers into making inferences to complement the available knowledge, mostly based on data from other areas or even from other species, such as different large carnivore species.

Although depending on the national legislation, most infrastructures are subjected to an Environmental Impact Assessment (EIA), which is the evaluation of the potential consequences that a development project can have on the environment (Geneletti, 2006). According to the International Institute for Sustainable Development (lisd.org), a EIA process includes several different stages, beginning with screening and scoping the situation, evaluating its environmental and socioeconomic impacts, identifying the most adequate mitigation measures, applying those measures and monitoring its effects. Furthermore, it's also important to differentiate between mitigation (i.e. minimizing the effects of a certain project) and compensation, which involves nulling the effects of a certain project, mainly when unforeseen impacts may remain (Arnett & May, 2016).

Additionally, mitigation hierarchy should be followed, which is a risk management framework used when developing and implementing projects that can potentially impact biodiversity and ecosystem services. Fundamentally, it's a way of making development projects more sustainable by mitigating its effects on biodiversity. There are four main sections in the mitigation hierarchy: avoidance, minimization, restoration and offsets. Avoidance is when measures are taken to prevent negative effects (e.g. no construction or site prioritization); minimization is reducing, as much as possible, negative impacts that are already expected or documented and can't be completely avoided; restoration is repairing already existing damage on the biodiversity and ecosystem, while offsets are actions applied to areas that were not impacted by a certain project so as to compensate for the damaged areas (csbi.org.uk).

In general, the section of mitigation hierarchy that is more commonly applied on infrastructure development targeting large carnivores is minimization, and more rarely, also avoidance and offsets. Based on available literature, six more particular types of mitigation measures have been applied to prevent impacts of infrastructure development on wildlife, and particularly on large carnivores: planning and design, protection of sensitive areas, spatio-temporal limitation of infrastructure use/construction, wildlife passages and habitat improvement and infrastructure decommission. Planning and design usually relates to the initial phase of infrastructure development (considered as avoidance in the mitigation hierarchy), when the infrastructure location or layout changed in a way that can minimize potential effects from the beginning (Passoni et al., 2017), although it may also incorporate changes applied to said infrastructure in order to minimize its effects. Protection of sensitive areas means avoiding disturbances, particularly during construction, to highly important habitat patches used by large carnivores (e.g. breeding sites) while spatio-temporal limitation of infrastructure use/construction considers minimization measures that prevent disturbance in areas or time periods that are crucial for large carnivores (e.g. closing access roads or safeguarding mating season) (Ferrão da Costa et al., 2018). Wildlife passages refers to the development of "green corridors", also including bridges and underpasses, with the intent of reconnecting fragmented habitats (van der Grift et al., 2013). As such, this minimization measure can be employed to mitigate the effects of roads, railways, fences or urban areas but is not exactly a suitable strategy to reduce the potential impacts of wind farms, for example. Habitat improvement (considered as offset in the mitigation hierarchy) is when one area is affected by a certain infrastructure and other areas are improved in order to somehow compensate the documented impacts (Maron et al., 2010). Hence, habitat improvement as a mitigation measure can be direct (when a certain effect is directly assessed on other areas, such as compensating the barrier effect of a certain road by developing wildlife corridors in other roads nearby or compensating habitat loss due to a certain infrastructure by improving habitat suitability in other areas) or indirect (when actions are developed to reduce threats or improve the conservation status of the impacted species, such as public awareness, prey improvement, damage prevention measures or reduction of human-caused mortality). Finally, infrastructure decommission (considered as restoration in the mitigation hierarchy) is when an infrastructure stops being used and is dismantled or removed in order to prevent further negative impacts on wildlife, something that has been mostly applied to dams from hydropower facilities or ski resorts (Botelho et al., 2017). Infrastructure decommission is increasingly considered with the goal of ecological restoration and not so much for the purposes of large carnivore conservation, although these species can clearly benefit from this mitigation measure.

Currently, the wide array of effects and behavioral responses on large carnivores resulting from infrastructure development as well as the highly variable EIA and mitigation procedures, are documented in several and scattered literature, including scientific publications, technical reports or national guidelines. This turns difficult to have a clear perception of this important topic for large carnivore conservation, particularly considering the socio-economic trends in Europe that predict a sharp increase in infrastructure development during the next decades (Rode et al., 2021). In this context, reviewing this available body of information is required as it can provide a better understanding of the effects of infrastructures on the several large carnivore species, as well as identify best practices and knowledge gaps in order to better mitigate potential impacts.

1.4. Goals and working hypothesis

The main goal of this study is to review the available knowledge on the effects and mitigation of infrastructure development on large carnivores, focusing mainly in Europe. More specifically, this study aims to: i) conduct an European-level characterization of the types of infrastructures known to affect the six species of European large carnivores; ii) evaluate the positive and negative effects that have been reported as well as the mitigation measures applied; determine the legal frameworks for EIA and mitigation/compensation procedures in each European country as well as the methodological approaches and biological indicators used to assess impacts of infrastructures on each of the target species.

The main working hypothesis of this study concerning distribution of publications per country are:

(1) all types of infrastructures potentially have a negative impact on each large carnivore species, given their susceptibility to human disturbance;

(2) countries where large carnivores are legally protected have more literature associated with infrastructure impacts and mitigation measures, due to legal requirements for EIA focusing on threatened wildlife;

(3) countries with higher human intervention (e.g. higher population density, economic development index and road network density) have more literature regarding infrastructure impacts and mitigation measures because of a stronger need to make human development compatible with large carnivore conservation;

(4) the home range of large carnivores is related with the amount of available literature on infrastructure effects since species with larger home ranges are more prone to face effects from human-made infrastructures;

Based on the information gathered by an extensive literature review and an online survey to experts, we expect to determine the major reported effects for each infrastructure type and large carnivore species as well as identify the best-practice procedures to address this important topic for wildlife conservation.

As a final note, this Master Thesis was conducted in the scope of a working group from Large Carnivore Initiative for Europe (LCIE: https://lcie.org/), related to “Impact of Infrastructure Development on Large Carnivores” and coordinated by the main supervisor (Francisco Álvares). LCIE is an IUCN/SSC Specialist Group constituted by experts on large carnivore research and conservation from 36 different nationalities.

2. Materials & Methods

2.1. Literature review

Data Collection

An extensive literature review was conducted to collect data on effects of infrastructures in each European large carnivore species, by focusing the following main components: a) type of infrastructure, b) positive and negative effects and c) applied mitigation measures. Data from literature review was collected using Google Search, Google Scholar, Web of Science, online Databases (e.g. LIFE projects) and reference lists in obtained publications, being complemented with contributions from large carnivore experts in Europe (LCIE members). Keywords used for the bibliographic search included the six European large carnivore species (including scientific and common names) as well as all infrastructure types, namely: Highways, Main/secondary roads, unpaved roads, unspecified roads, urban areas, Fences, Windfarms, Railways, Power lines, Mines, Pipelines and Touristic facilities, including Resorts, Cabins and Viewpoints. Two main types of publications were considered separately: a) scientific publications including SCI articles, book chapters and dissertations such as MSc, and PhD theses; and b) technical reports from conservation projects (Annex S1).

Every publication considered adequate was screened for date of publication, country, species and infrastructure type(s) studied, documented effects on large carnivores, study area (country), type of publication, type of responses from large carnivores and proposed mitigation measures, although the latter two topics were not mentioned in all publications.

Literature review was mostly focused in Europe but since several compiled publications were from North America (USA and Canada), this literature was analyzed separately to allow a comparison of bibliometric patterns between continents. For North American literature was only considered the 3 species of large carnivores that are also occurring in Europe, namely: grey wolf, grizzly bear and wolverine. However, it´s important to note that the literature review for North America was not as detailed and thoughtful as for Europe, which was the main target of this study.

Data analysis

The information gathered on the literature reviews was organized in databases using Microsoft Excel. A general descriptive analysis was conducted based on the number of compiled scientific publications per decade, type of publication, country/region, large carnivore species, infrastructure type, documented effects on large carnivores, kind of responses from large carnivores and proposed mitigation measures.

Documented effects on large carnivores were categorized as: Occurrence, Habitat selection (for breeding or resting), Habitat selection (for foraging), Movements, Reproduction, Mortality, Other behavioral responses, Stress and genetic diversity.

Responses to infrastructures were categorized as: Negative, Positive or Not clear.

Mitigation measures when proposed, were categorized as: Planning & design, Protection of sensitive areas, Spatial-temporal limitation of infrastructure use/construction period, Wildlife passages, Habitat improvement (either direct or indirect) and Infrastructure decommission.

The conservation projects were analyzed separately although in an identical way, on the number of projects per decade, country, species, type of publication (i.e. funding program) and infrastructure types considered, along with mitigations measures applied.

To identify potential determinants related to the number of scientific publications in Europe, Generalized Linear Models (GLM) were used, with the number of compiled publications per species and country in Europe as dependent variable, with gamma distribution and log-link function. Only countries with publications were considered in each analysis. Two different sets of predictors were considered: (1) traits of large carnivore species in each country within its range (protection status, population size); (2) ecological and socio-economic traits from each country (road network density, percentage of forest cover, human population density and GDP per capita – Gross Domestic Product, in euros) (Table 7). Models considered 3 different dependent variables: i) number of compiled publications reporting effects of infrastructures on large carnivores; ii) number of compiled publications reporting the use of mitigation measures; and iii) number of compiled publications per species for each large carnivore species.

Table 7 Unit and sources for the variables used in the modelling apporach

Variable	Unit	Source
Population density	population size/km2	statisticstimes.com
Forest cover	km2	theglobaleconomy.com
GDP per capita	euros	focuseconomics.com
Road network density	km	worlddata.info
Large carnivores home range	km2	lcie.org

Furthermore, to evaluate the relation of home range size of each large carnivore species with the number of publications on infrastructure effects, a multiple regression was used with the number of publications as the dependent variable and the average home range of large carnivore species (considering both sexes) as predictors.

Finally, to assess similarity patterns between European countries considering ecological and socioeconomic traits, and also the number of publications reporting mitigation measures per country, it was conducted a cluster analysis was conducted using a between-groups (BEAVERAGE) method of clustering and City Block as distance measure. Variables included were human population density, forest cover percentage, road network density and number of publications mentioning mitigation measures. All statistical analysis were conducted using SPSS 28 (IBM Inc.).

2.2.Expert-based questionnaire

Data collection

An online questionnaire focusing on Environmental Impact Assessment (EIA) and mitigation measures for infrastructure development targeting large carnivores in European countries was developed using Google Forms (Annex S2) and sent to experts on large carnivores, namely to all members of the Large Carnivore Initiative for Europe (LCIE) and other Portuguese experts on this topic. Online questionnaires are increasingly being used to assess various research topics, as they represent an easier and less costly way of gathering systematic information from a large sample and wide spatial scale (Hartman & Craig, 2019). Therefore, this tool is expected to allow a better understanding of the frameworks that are currently employed in each European country for assessing infrastructure impact on large carnivores.

The survey included 17 questions regarding legal frameworks and procedures for EIA as well as mitigation measures being employed in each European country and for each large carnivore species. Questions also focused on the different sampling methods used for impact evaluation targeting large carnivores.

Data analysis

The information gathered on the responses to the expert-based questionnaire were organized and analyzed using Google Forms' tools and Microsoft Excel. A general descriptive analysis was conducted based on the number of responses, considering country and main procedures for EIA and mitigation measures.

3. Results

3.1. Literature review

Overall, the literature review concerning effects and mitigation of infrastructures on large carnivores resulted in the compilation of 138 scientific publications and 21 conservation projects focusing in Europe, as well as 37 scientific publications focusing in North America (Annex S1).

3.1.1. Scientific publications in Europe

Considering the review of 138 publications in Europe, the vast majority were scientific articles (88%; n=121) published in the current millennium, especially from 2010 to 2019 (47%; n=65) (Figure 9).

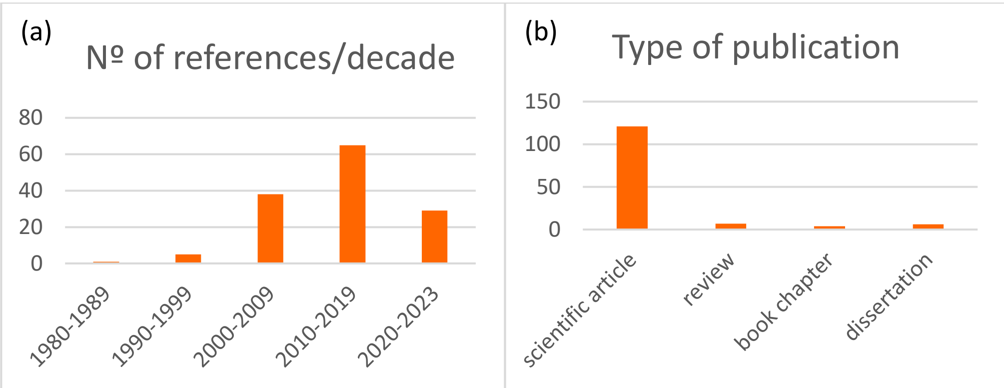

Figure 9: (a) Number of reviewed publications in each decade; (b) Type of reviewed publications

Regarding the number of publications per European country, Spain was the one with more scientific studies (16%; n=22), followed by Sweden (15%; n=21) and Norway (14%; n=19). Italy, Croatia, Poland and Slovenia were also associated with a reasonable number of scientific studies, presenting each more than 10 scientific publications. In contrary, countries such as France, Denmark, Austria, Montenegro, Estonia and Russia showed only 1 publication each. Additionally, there were 4 studies at a continental scale – mainly addressing the effect of urban areas in Europe as a whole -, as well as 2 global studies addressing the effects of linear transport infrastructures, that also included Europe (Figure 10).

Poland was the country associated with more reviewed publications proposing mitigation measures (n=9), followed by Sweden and Croatia (n=7 in both cases).

Germany, Bulgaria, Denmark and Montenegro had no reviewed publications referencing mitigation measures (Figure 10).

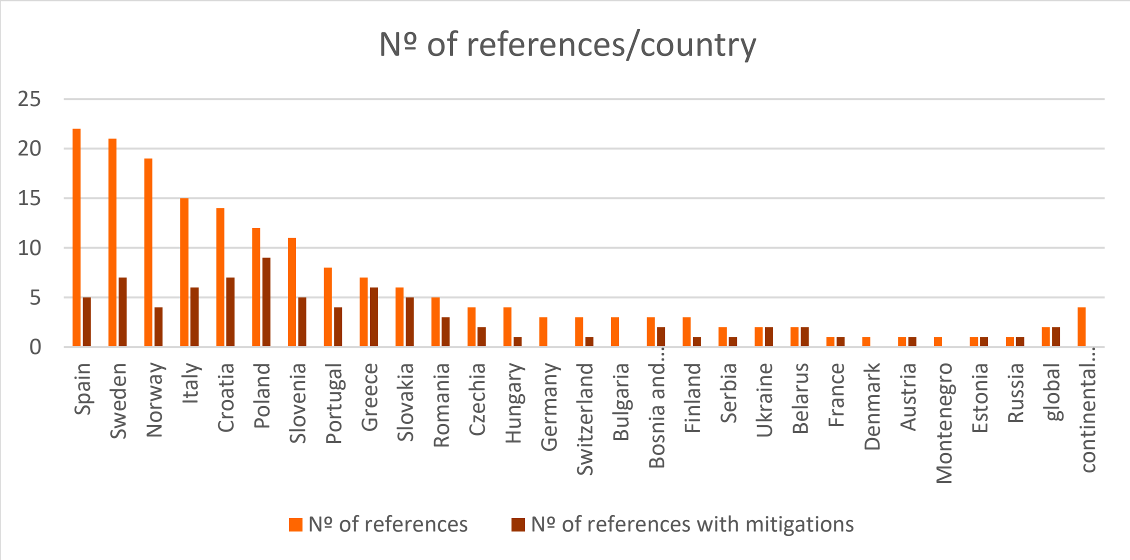

Figure 10: Number of total reviewed publications and number of reviewed publications recommending mitigation measures per country

As for the target species, the brown bear (44%; n=61), followed by the grey wolf (38%, n=53) were the ones with more studies addressing effects of infrastructures. On the other hand, the Iberian lynx, the wolverine and the golden jackal were each the focus of less than 20 scientific publications, with the wolverine being the least documented species (4%, n=5) (Figure 11).

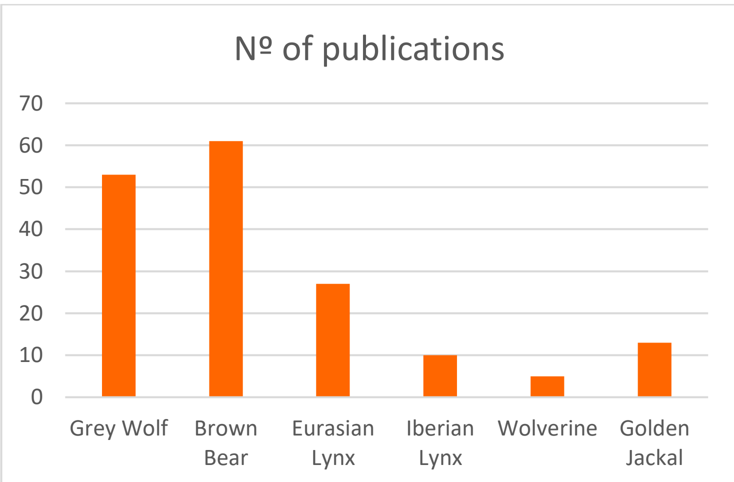

Figure 11: Number of reviewed publications per each large carnivore species

Regarding the infrastructure types that are addressed in scientific publications, it was noticeable that roads, in general, were the most studied, particularly main roads that comprised 46% of the reviewed publications (Table 8). Over 20% of the reviewed publications did not elaborate on the type of road that was studied, being considered as unspecified roads. Other linear infrastructures, such as railways, were mentioned in only 15% of the reviewed publications. Urban areas were the second most commonly studied infrastructure type, being referenced in 49% of the scientific publications. On the other hand, all the other infrastructure types were only present in less than 5% of the publications, with mines, resorts and viewpoints appearing in one single study each.

Table 8: Number and percentage of reviewed publications addressing each infrastructure type

Infrastructure	References
Highway	N=27 (19%)
Main roads	N=64 (46%)
Secondary roads	N=23 (16%)
Unpaved roads	N=28 (20%)
Railways	N=21 (15%)
Urban areas	N=68 (48%)
Fences	N=5 (3%)
Wind farms	N=3 (2%)
Power lines	N=2 (1%)
Mines	N=1 (0,7%)
Resorts	N=1 (0,7%)
Cabins	N=3 (2%)
Viewpoints	N=1 (0,7%)
Hydropower complex	N=2 (1%)
Roads (unspecified)	N=30 (21%)

Concerning reported effects on large carnivores, in general, most scientific studies focused on occurrence and movements while reproduction, other behavioral responses, stress and genetic diversity have received clearly less attention, with very few studies evaluating these parameters (Figure 12). The only two studies reporting effects on reproduction were focused on wolves considering the effect of wind farms. Other behavioral responses were analyzed, mostly regarding bears and their response to different types of infrastructures, such as main roads, secondary roads, unpaved roads, urban areas and viewpoints. Additionally, behavioral responses to urban areas were also studied in relation to the golden jackal. Effects on stress were evaluated in relation to the wolf (concerning its response to main roads and urban areas) and the bear (pertaining to urban areas). Studies concerning the effects on genetic diversity were all focused on bears, regarding main roads, railways and unspecified road categories. It was also evident that effects on habitat selection targeting breeding/resting sites were more frequently studied than those pertaining to foraging sites. Also, most of the studies addressing effects on mortality involved linear transport infrastructures, and were reported for all large carnivore species.

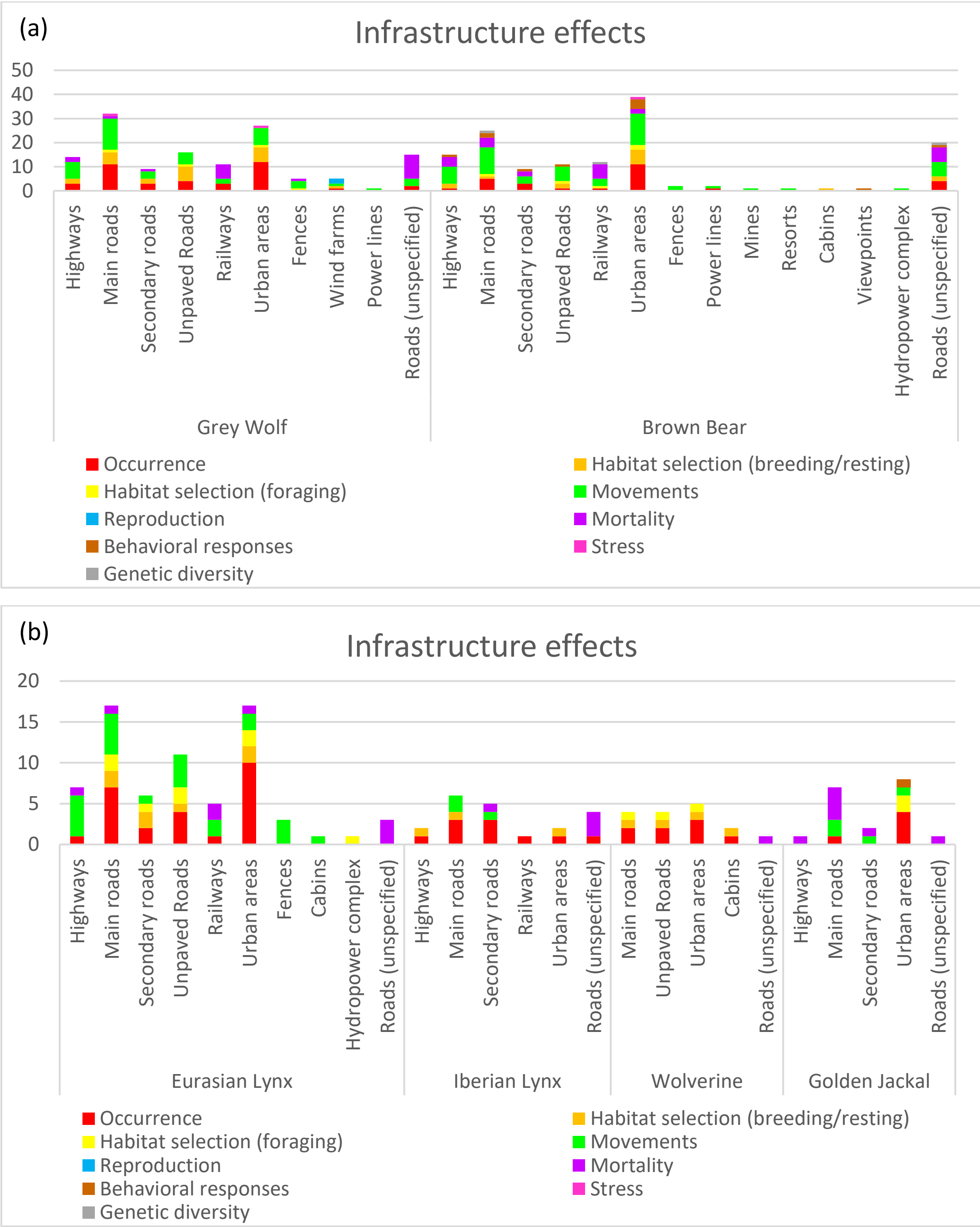

Figure 12: Number of reviewed publications addressing effects of infrastructures on different biological traits, for each large carnivore species in Europe (a) grey wolf and brown bear; (b) Eurasian lynx, Iberian lynx, wolverine and golden jackal

Regarding the type of response, all large carnivores showed mostly negative responses to infrastructures, although in several cases, positive or neutral/inconclusive responses were also reported (Figure 13). Positive responses were reported mostly to urban areas and linear infrastructures, such as low traffic roads, and involving all carnivore species except Iberian lynx. With much less expression, positive responses were also reported to power lines and viewpoints for brown bears and to fences for wolves. It´s relevant to note that in some cases responses to anthropogenic infrastructures were more positive than negative, such as unpaved roads for Eurasian lynx, urban areas for golden jackals and viewpoints for brown bears (Figure 13). In addition, only neutral or inconclusive responses were reported to power lines for wolf, to fences for brown bear and Eurasian lynx and to unspecified roads for wolverine.

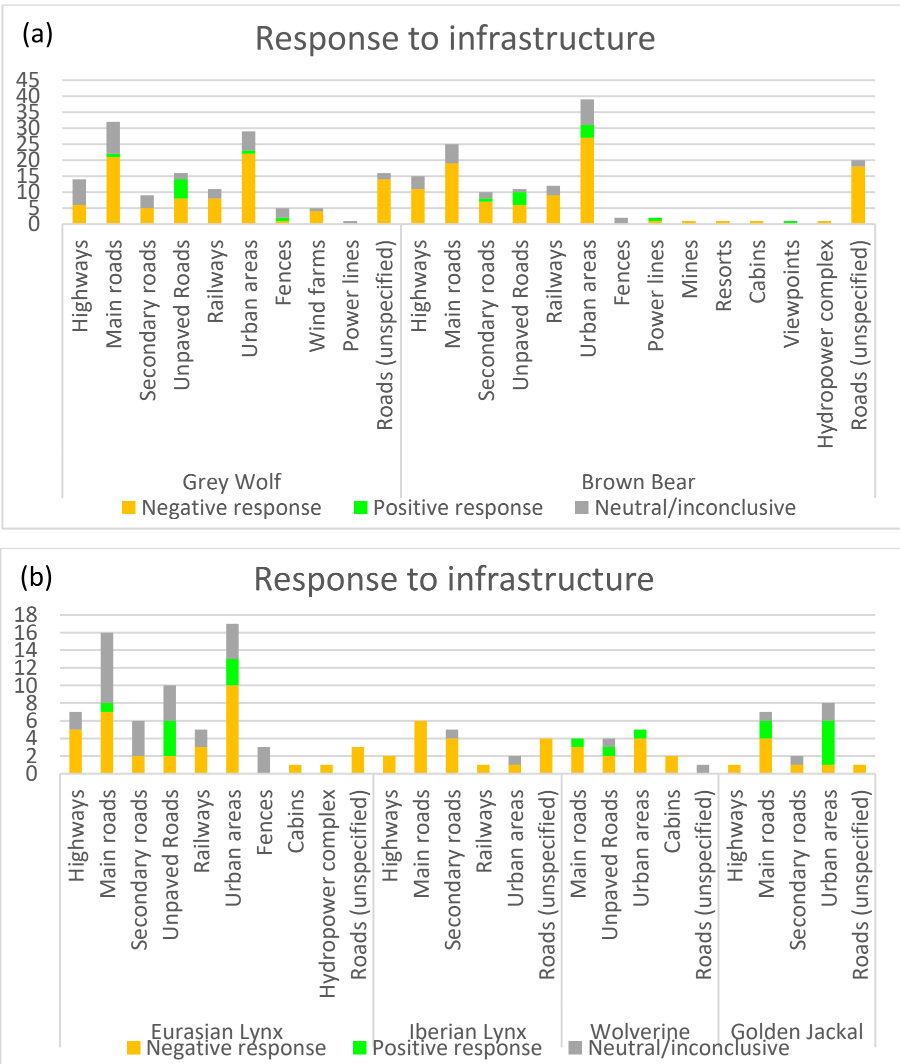

Figure 13: Number of reviewed publications reporting the type of responses to each infrastructure type and for each large carnivore species in Europe (a) grey wolf and brown bear; (b) Eurasian lynx, Iberian lynx, wolverine and golden jackal

Most scientific publications did not recommend actual measures to mitigate the effect of infrastructures on large carnivores, although in several cases measures were suggested for all target species (Figure 14). Curiously, the species with the least number of reviewed studies, the wolverine, had the higher percentage of proposed mitigation measures in relation to total number of references. Most of the proposed mitigation measures were associated with roads in general – especially main roads –, which were also the most reported infrastructure. For less reported infrastructures such as mines, hydropower complex and viewpoints, no mitigation measures were proposed, while the single publication mentioning touristic resorts did propose mitigation measures for brown bear (Figure 14). Scientific publications reporting effects from wind farms and fences also provided potential mitigation measures more often than not, and mostly for wolf, bear and Eurasian lynx.

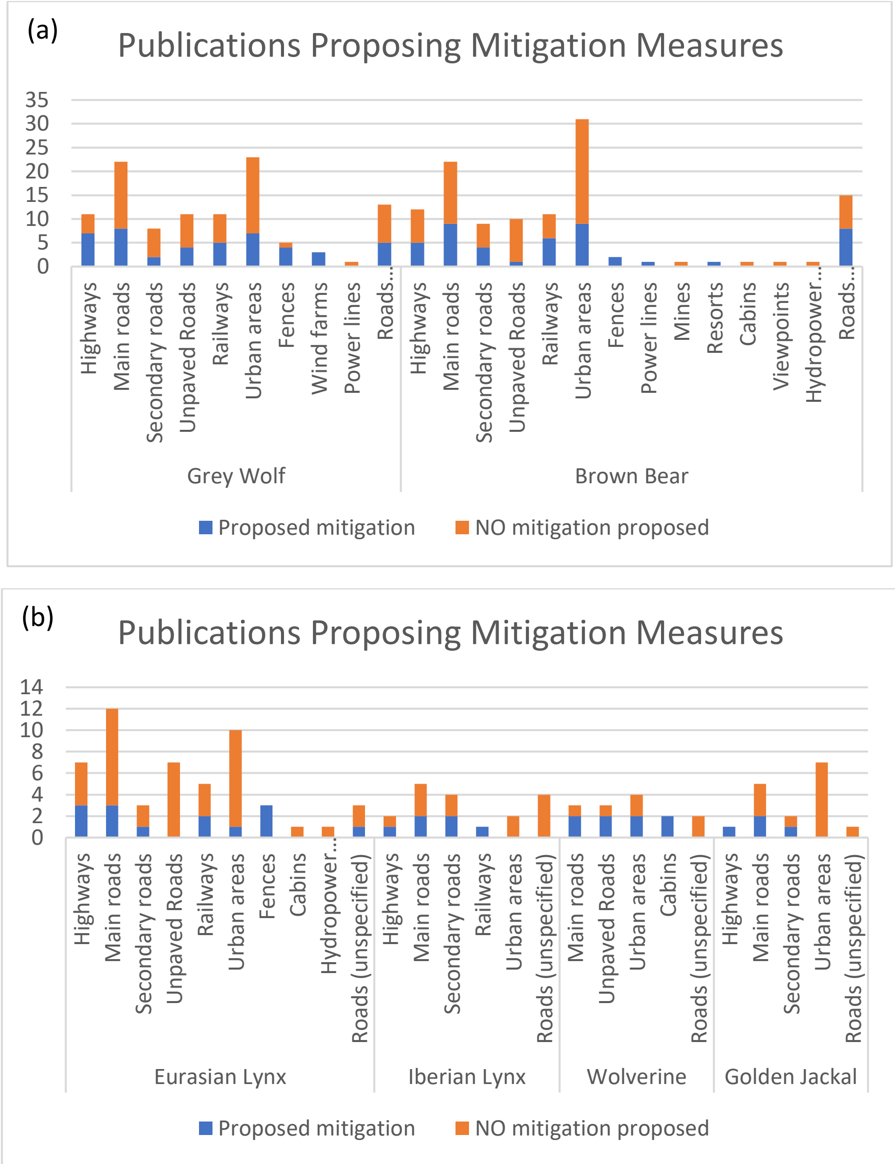

Figure 14: Number of reviewed publications recommending mitigation measures to each infrastructure type and for each large carnivore species (a) grey wolf and brown bear; (b) Eurasian lynx, Iberian lynx, wolverine and golden jackal

Concerning the type of mitigation measures that were recommended, planning & design was the most proposed one to all infrastructure types and for all large carnivore species, while infrastructure decommission received the least references. Wildlife passages were the second most suggested mitigation measure for all target species and it was proposed not only to linear infrastructures, such as roads, railways and fences, but also to wind farms and urban areas, particularly for wolves. Overall, other mitigation measures such as protection of sensitive areas and spatio-temporal limitations during use or construction were reported to several types of infrastructures and for all large carnivore species (except Iberian lynx), while offset habitat improvement, either direct or indirect, was suggested more rarely and mainly for wolves and brown bears (Figure 15).

Figure 15: Number of reviewed publications recommending specific mitigation measures to each infrastructure type and for each large carnivore species (a) grey wolf and brown bear; (b) Eurasian lynx, Iberian lynx, wolverine and golden jackal

3.1.2. Determinants for scientific publications per species and country

The model for grey wolf was significant (p=0,026) (Annex S4) and revealed that the number of wolf publications per country was explained by the wolf's protection status (B=-1,469; B"not protected"=-1,393, for B"protected"=0) and road network density at a national level (B=0,557) (Table 9) (Annex S4).

Models for the brown bear (p=0,135) and the Eurasian lynx (p=0,165) were not significant (Annex S4). Additionally, due to species limited range covering few countries, for wolverine and Iberian lynx, it was not possible to perform the tests country on country variation for wolverine and Iberian lynx.

Table 9: Test of the number of publications on wolves per country as determined by protection status, forest cover percentage, road network density and wolf population size using a Generalized Linear Model

Tests of Model Effects

	Type III		
Source	Wald Chi-Square	df	Sig.
(Intercept)	.001	1	.979
Wolf status	12.209	2	.002
Forest cover percentage	2.150	1	.143
Road network density	4.636	1	.031
Wolf pop	2.448	1	.118

Dependent Variable: Wolf publications
Model: (Intercept), Wolf status, Forest cover percentage, Road network density, Wolf pop

The model considering the golden jackal was significant (p=0,024) but none of the predictors explained a sufficient part of the variation in the number of jackal publications. However, road network density was almost significant (Table 10).

Table 10: Test of the number of publications on golden jackals per country as determined by protection status, forest cover percentage, road network density and jackal population size using a Generalized Linear Model

Tests of Model Effects

	Type III		
Source	Wald Chi-Square	df	Sig.
(Intercept)	2.110	1	.146
Jackal status	2.835	2	.242
Forest cover percentage	2.134	1	.144
Road network density	3.672	1	.055

Dependent Variable: Jackal publications
Model: (Intercept), Jackal status, Forest cover percentage, Road network density

Models for testing the influence of countries traits (forest cover, road network and the species population size and protected status) in the number of publications proposing mitigation measures were not possible in the wolverine and Iberian lynx cases once more, due to their limited distribution. Furthermore, models for brown bear (p=0,695), Eurasian lynx (p=0,503) and golden jackal (p=0,330) were all non-significant. Model for the wolf was significant (p=0,038), showing that the number of publications proposing mitigation measures was explained by the wolf's protection status at a national level (p=0,002; B=-1,522; B"not protected"=-1,030; B"protected"=0) (Table 11) (Annex S4).

Table 11: Test of the number of publications mentioning mitigation measures per country as determined by protection status, forest cover percentage, road network density and wolf population size using a Generalized Linear Model

Tests of Model Effects

Source	Type III Wald Chi-Square	df	Sig.
(Intercept)	.450	1	.502
Wolf status	12.353	2	.002
Forest cover percentage	.692	1	.405
Road network density	3.521	1	.061
Wolf pop	2.971	1	.085

Dependent Variable: Mitigation measures
Model: (Intercept), Wolf status, Forest cover percentage, Road network density, Wolf pop

Regarding the influence of home range size in the number of reviewed publications, the multiple regression revealed no significant effect (Table 12).

Table 12: Test of the number of publications per country in relation to large carnivore species home ranges using multiple regression

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.748[a]	.560	.266	20.242

a. Predictors: (Constant), HomeR_F, HomeR_M

b. Dependent Variable: Public

Including GDP and human population density in the modelling approach had no effect, as the two variables were never significant, neither affected significances of the other predictors, so that those results were not presented here.

Clustering countries as a function of publications and mitigation measures

The cluster analysis revealed that Spain is isolated (likely associated with a large amount of publications) and Finland is separated from the other Scandinavian countries (Norway and Sweden; possibly for being associated with a smaller number of publications mentioning mitigation measures). Portugal is grouped several countries from central and western Europe, although it appears isolated inside that group, which may be related to the fact that Portugal is associated with more publications mentioning mitigation measures than the remaining countries (Figure 16).

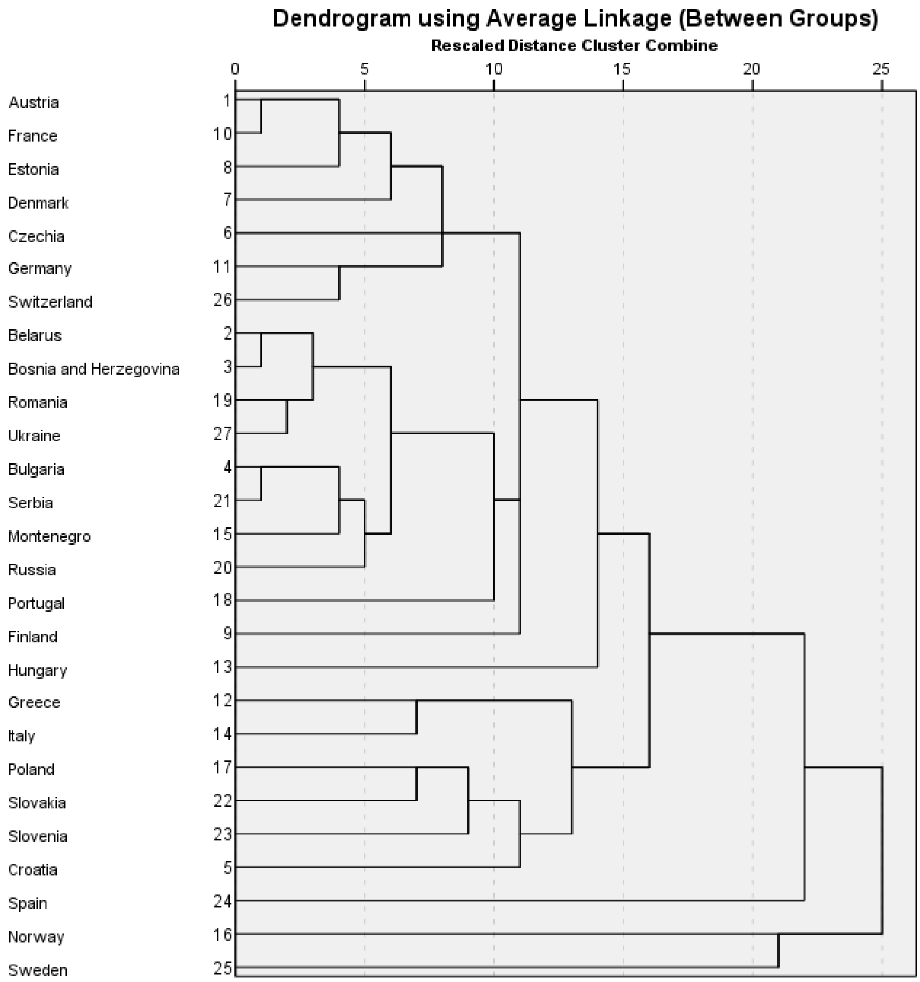

Figure 16: Dendrogram testing relationship between European countries considering GDP, forest cover percentage, road network density, human population density, number of reviewed publications mentioning mitigation measures and number of publications per species.

3.1.3. Conservation projects in Europe

Considering the review of 21 conservation projects in Europe, mostly were developed between 2010 and 2019 (similarly to scientific publications), and almost all belonging to the LIFE funding program, with only one, ConnectGREEN project, being by Interreg (Figure 17).

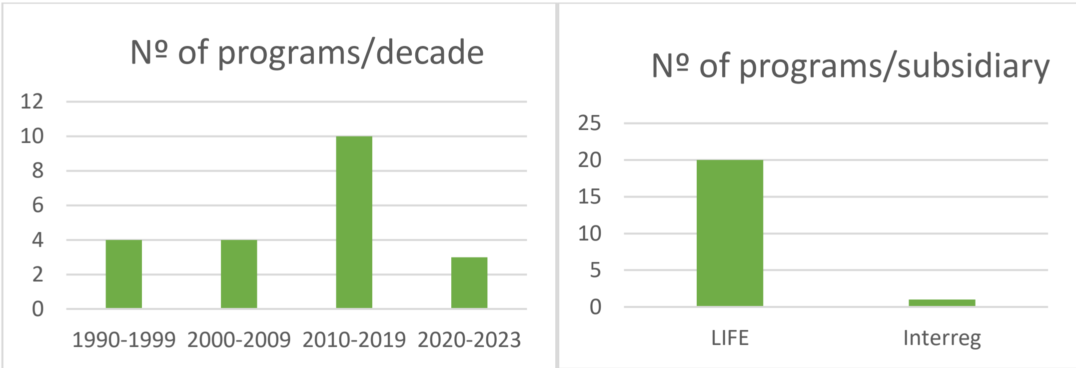

Figure 17: (a) Number of reviewed conservation projects developed per decade; (b) number of reviewed conservation projects per funding program

Italy and Greece were the countries associated with more conservation projects (each n=7; 33%), followed by Portugal (n=5; 24%) and Spain (n=5; 24%). Almost half of the reported countries on the list (n=8; 38%)were part of only one project and 9 (43%) projects included more than one country (Figure 18).

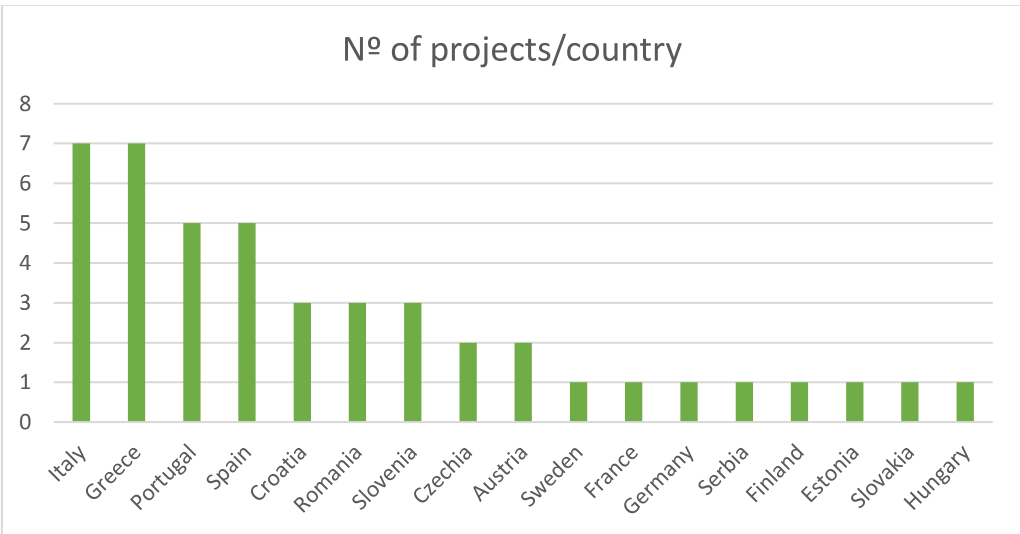

Figure 18: Number of reviewed conservation projects per country

Similar to the reviewed scientific publications, the grey wolf and the brown bear were the most common target species, although the wolf (n=12; 57%) was associated with more conservation projects than the bear (n=10; 48%). The Iberian lynx came in third (n=4; 19%), surpassing the far more common Eurasian lynx (n=3; 14%). Conservation projects concerning effects or mitigation of infrastructures on wolverines and golden jackals were not found (Figure 19).

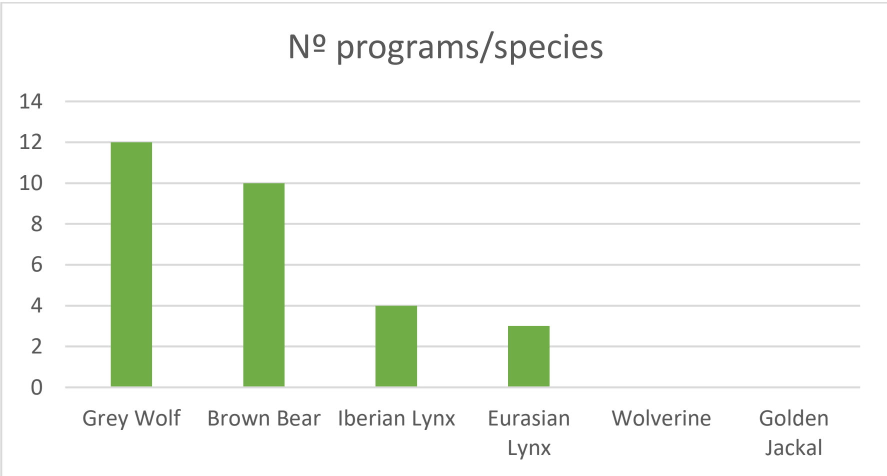

Figure 19: Number of programs focusing on each LC species

Concerning infrastructure types (Figure 20), roads were the most predominant in conservation projects (n=17, 81%), although with no distinction between road types, since the reviewed projects do not make these kind of specifications. Urban areas are mentioned in 3 conservation projects (14%) while railways appear in 2 (9%), all of which focusing on wolves and bears. The potential effect of recreational cabins was included in one conservation project that included wolf, bear and Eurasian lynx. Finally, fences were only taken into account in a single conservation project, associated with wolves.

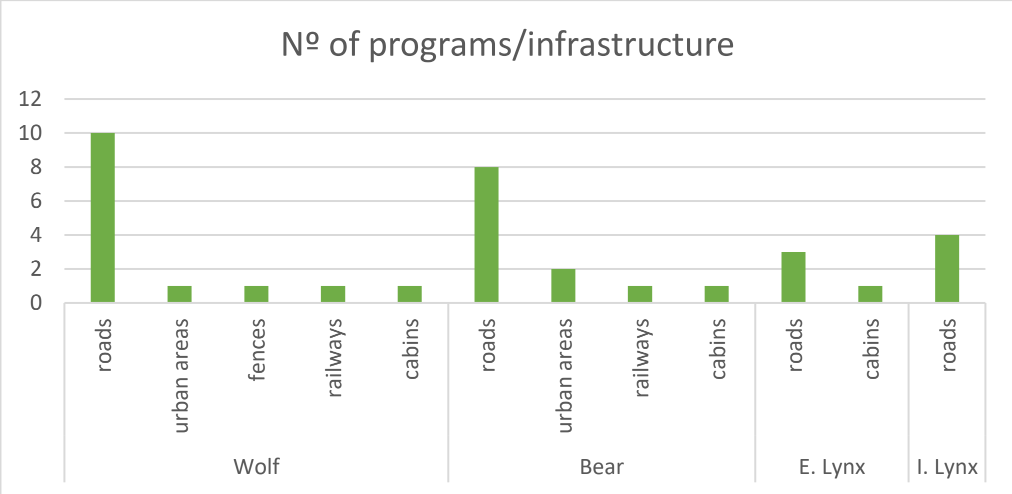

Figure 20: Number of reviewed conservation projects focusing each infrastructure type and each large carnivore species

Every conservation project either suggested or actually applied some type of mitigation measure, with indirect habitat improvement being the most common (Figure 21). This was mainly associated with public awareness campaigns along with improvement of prey availability, with the latter being especially common when pertaining to the Iberian lynx. Wildlife passages were strictly associated with linear transport infrastructures, something that was also verified in the case of infrastructure decommission, which was associated with old forest roads. Mitigation measures related to spatio-temporal limitation of infrastructure use/construction and protection of sensitive areas were absent in the reviewed conservation projects.

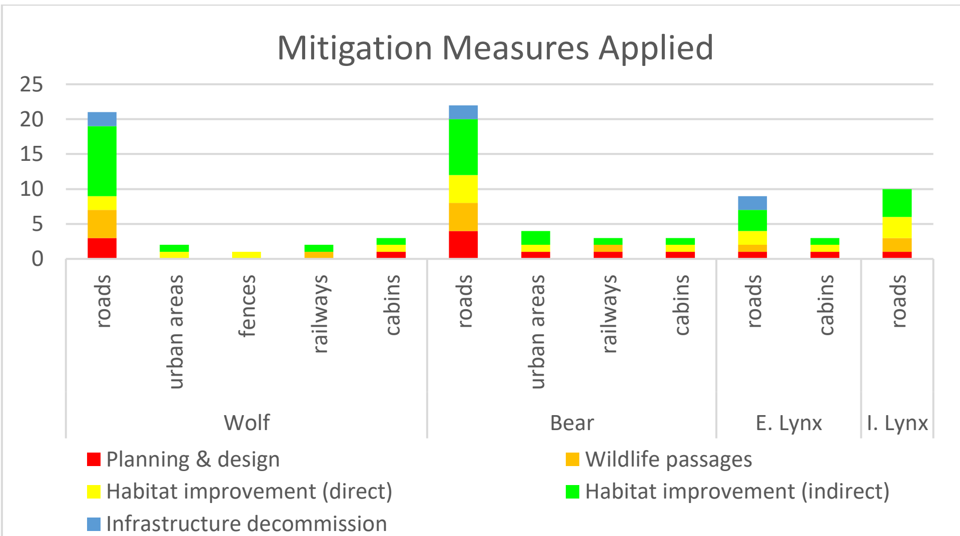

Figure 21: Number of reviewed conservation projects that applied specific mitigation measures considering each infrastructure type and each large carnivore species

3.1.4. Scientific publications in North America

Regarding the 37 scientific publications concerning effects and mitigation of infrastructures on large carnivores with a focus in North America (considering only grey wolf, grizzly bear and wolverine), one was a review paper, another was a dissertation and the remaining were scientific articles. Overall, 30 publications were focused in Canada (81%) and 8 in the United States of America (22%). Similar to the European literature review, most references (n=25; 67%) were published after 2010 (Figure 22).

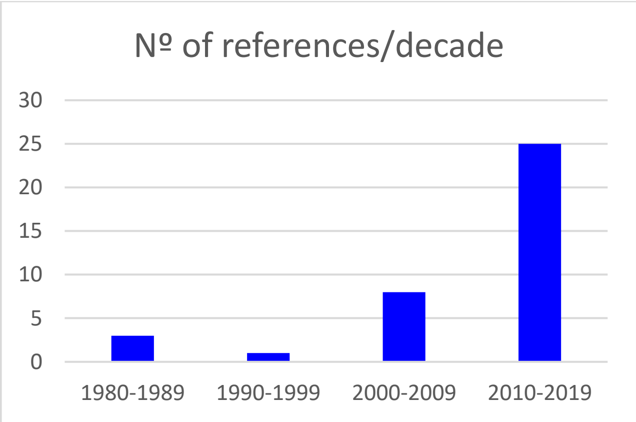

Figure 22: Number of reviewed publications from North America per decade

Bears were the most mentioned species (n=24; 65%), followed by wolves (n=12; 32%), while the wolverine was the target species with the least scientific literature in North America (n=4; 11%).

Several kinds of roads, particularly highways, were the most reported infrastructure by far (n=34; 92%), followed by railways (n=5; 13%). Other reported infrastructures included urban areas, power lines, mines and pipelines, which weren't reported in any reviewed publication focusing in Europe (Figure 23).

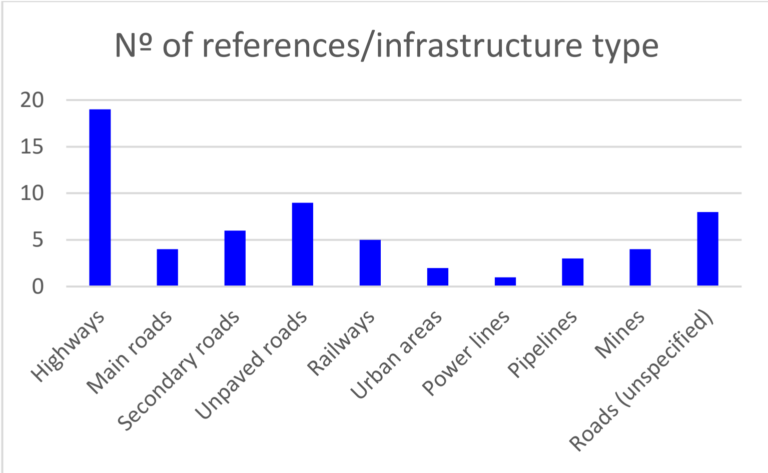

Figure 23: Number of reviewed publications from North America addressing each infrastructure type

The most studied biological trait in the reviewed publications from North America was movements, while reproduction was only addressed in one single publication related to the effect of mines in grizzly bears (Figure 24). Effects on habitat selection including resting and breeding sites as well as on genetic diversity were also analyzed in few publications focusing on mines for bears in the former's case, and on highways for bears and wolverines in the latter. Mortality was more associated with linear transport infrastructures although one publication assessed this parameter related to urban areas, for bears. Reviewed publications addressing pipelines, which were all related to wolves, focused on occurrence, habitat selection for foraging sites and, specially, on movements.

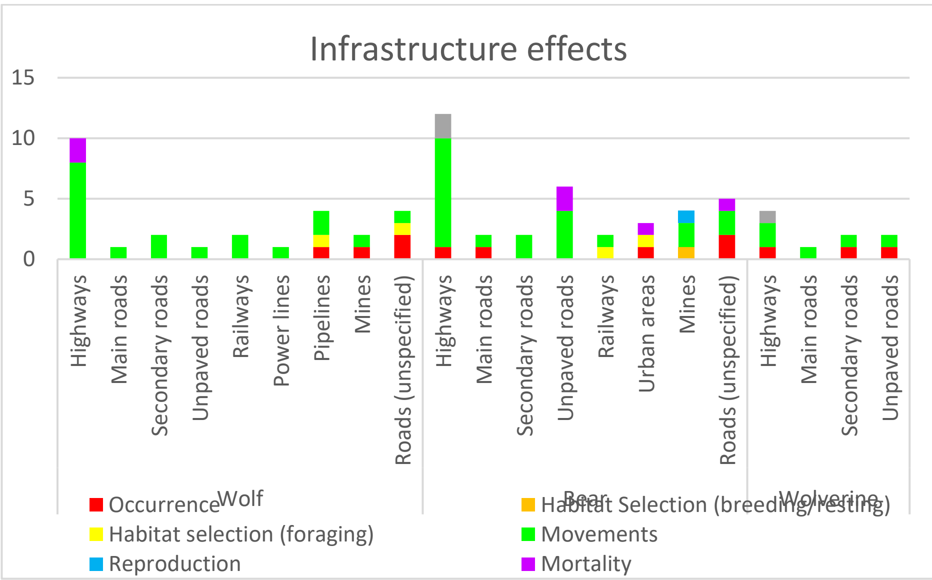

Figure 24: Number of reviewed publications from North America addressing different biological traits of each large carnivore species in relation to each infrastructure type

The vast majority of reviewed publications in North America described negative responses of large carnivores to anthropogenic infrastructures, with responses from grizzly bears to highways being particularly negative. Positive responses were only reported from wolves to unpaved roads and power lines, while inconclusive responses were reported only for wolverine to several types of roads (Figure 25).

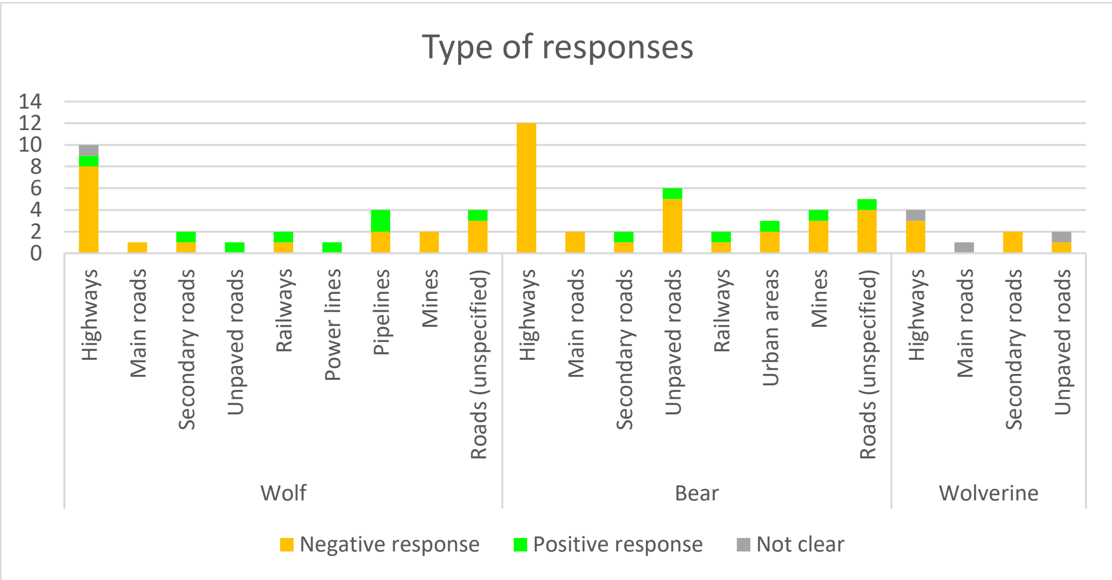

Figure 25: Number of reviewed publications from North America reporting responses of each large carnivore species to different infrastructure types

All publications concerning effects of infrastructures on the wolverine proposed some type of mitigation measure (Figure 26). Similarly, for grizzly bears, most reviewed publications proposed mitigation measures to all infrastructures except to urban areas. As for wolves, almost all references addressing highways and main roads proposed some type of mitigation, while publications evaluating effects to unpaved roads, unspecified types of roads, power lines, pipelines and mines did not mention any mitigation measure.

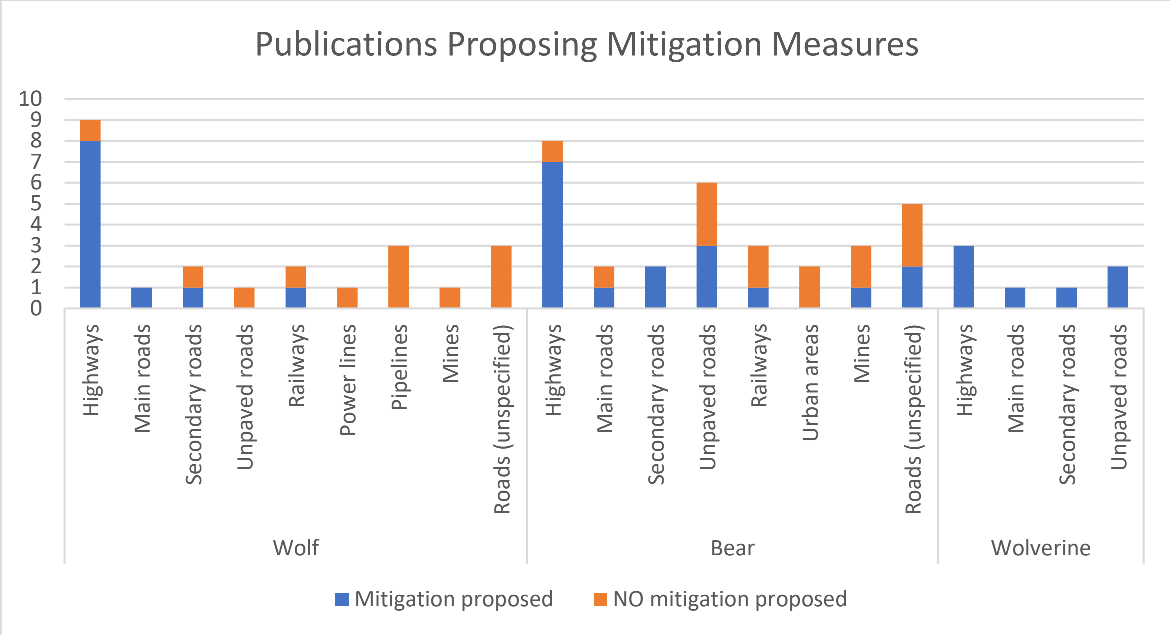

Figure 26: Number of reviewed publications from North America proposing mitigation measures for each infrastructure type

Planning & design was the most commonly proposed mitigation measure in North America for all types of infrastructures and across the target species, while infrastructure decommission was only referenced to low traffic roads for bear and wolverine (Figure 27). As expected, wildlife passages received a considerable amount of attention on publications addressing highways, both for wolves and grizzly bears. Other measures, such as protection of sensitive areas, spatio-temporal limitations and habitat improvement were mentioned mostly to mitigate effects of several kinds of roads for all species, and also to mitigate effects of railways and mines for bears (Figure 27).

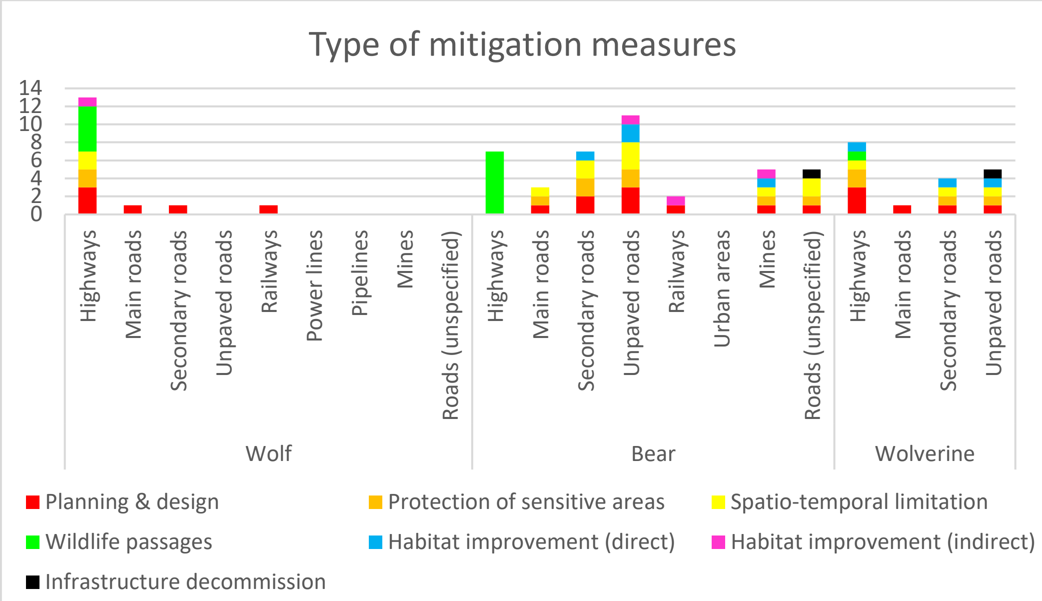

Figure 27: Number of reviewed publications from North America that propose specific mitigation measures type to each infrastructure and for each large carnivore species

3.2. Expert-based questionnaire

There were 12 responses to the online survey, representing the following countries: Albania, Croatia, France, Germany, Italy, Latvia, Portugal, Romania, Serbia, Slovenia, Spain and Turkey (Annex S3). Only in Turkey was asserted that EIA didn't take large carnivore species into consideration. For the remaining 11 countries, the main requirements to carry out an EIA concerning large carnivores had a wide variation, with Italy and Romania mostly focusing on protected areas while Portugal, Spain, France and Croatia consider all species range. (Table 13).

Table 13: Requirements to carry out Environmental Impact Assessments focusing on large carnivores in each European country

Country	Requirements for EIA on large carnivores (LC)
Albania	not specified
Croatia	Required for most EIA on new infrastructures in LC range; not guaranteed to favor LC
France	"Avoid, Reduce, Compensate" principle. Particularly applied to transport infrastructures and concerning protected species (which include LC). Applied in and outside protected areas
Germany	Species' protection status is highly important
Italy	Especially employed in Natura 2000 sites, if reproductive sites are concerned
Latvia	Particularly takes into account the protected species (which includes LC)
Portugal	Any infrastructure developed inside the known range of LC will be subject to EIA concerning LC
Romania	Particularly when concerning roads and protected areas
Serbia	No specific requirements (general approach as for other wildlife is requested)
Slovenia	Throughout the range of LC species and in areas where they are expected to expand.
Spain	Can be employed anywhere that an infrastructure may have an impact on LC population

Additionally, the species' protection status and population size at national level were mentioned on 10 countries (all except Turkey and Latvia) as major influencing factors on deciding whether an EIA focusing on large carnivores was necessary, making it the most mentioned factor. Still, 9 countries asserted that EIA was a common procedure in their country for all infrastructure and wildlife species while 7 countries claimed that the size and location of the infrastructures had major influence in the decision to carry out an EIA, regardless of the protected status of the affected species. One country (Spain) highlighted that EIA was conducted for any wildlife species but was especially important when concerning protected species. Protected areas (such as Natura 2000 sites) was also mentioned once, for Croatia, as a main factor to decide an EIA. Furthermore, in Germany, EIA was a common procedure for wildlife species, with species protected status also having influence on the matter, although it was mentioned that "exceptions are almost always permissible" when public welfare is involved.

As for the target species for EIA, all 12 countries mentioned the grey wolf, while the brown bear and the Eurasian lynx were referenced in 10 and 9 countries, respectively. The golden jackal received considerably less mentions, with 4 countries, while the Iberian lynx was obviously only mentioned for Portugal and Spain. On the other hand, the wolverine was not mentioned at all as no response was obtained in countries where this species occurs.

Regarding infrastructure types associated with EIA focusing on large carnivores in each country, roads (n=11; 92%) received the most mentions (although road types were not specified), followed by railways (n=9; 75%), wind farms and power lines (n=8, for both) (Figure 28). Several other infrastructures less obvious, such as pipelines (Serbia and Albania), dumps (Serbia), industrial factories (Serbia) and waterway transport (France) were also mentioned as being target for EIA focusing large carnivores. Additionally, Portugal and Albania referenced solar power plants, an infrastructure type that has been becoming increasingly common but was absent from reviewed publications. Latvia did not specify any infrastructure type, claiming only that infrastructures associated with EIA were "defined by law".

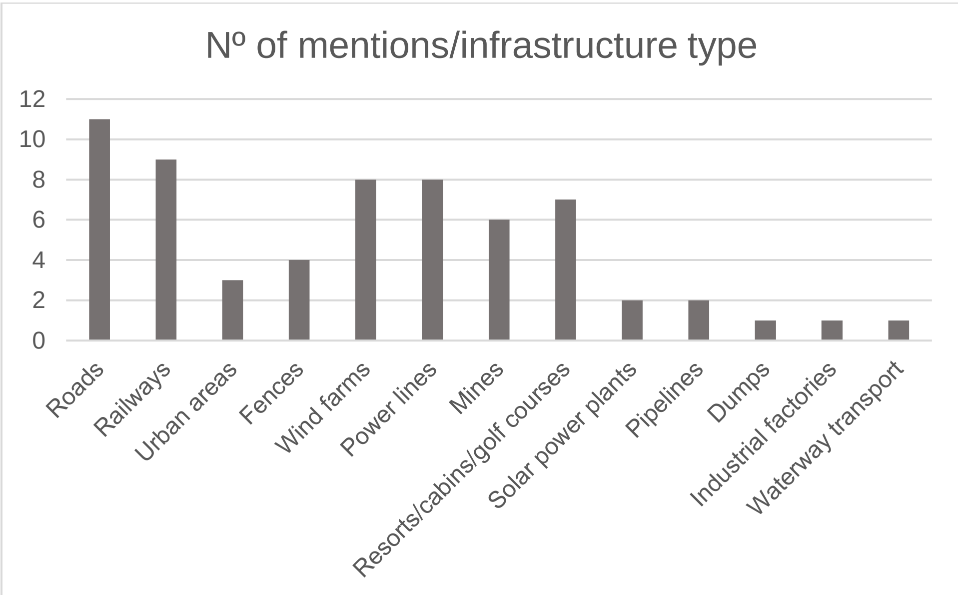

Figure 28: Number of answers in the online survey mentioning each infrastructure type

Occurrence was the biological trait mentioned to be the most assessed in EIA regarding large carnivores (n=10, 83%), followed by mortality, movements, reproduction and habitat selection (specifically concerning breeding and resting sites) (Figure 29).

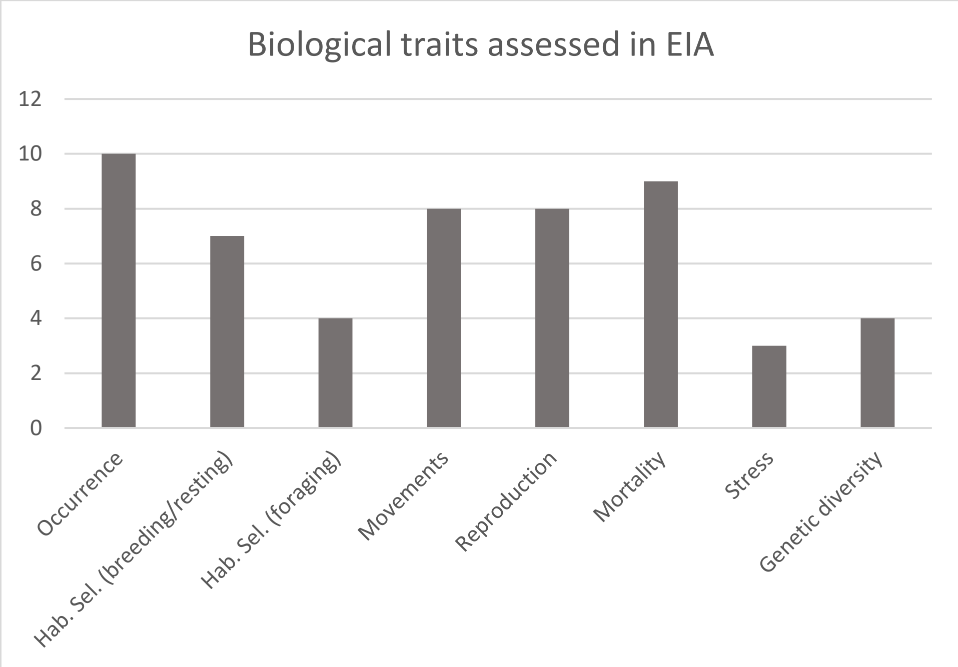

Figure 29: Number of answers in the online survey mentioning each biological trait

Regarding analytical approaches used for EIA during post-monitoring, the BACI approach ("Before-After Control-Impact) was the most used (5 countries; 42%), followed by "Cumulative effects", which was mentioned in 4 countries (33%). "Exclusion effect", on the other hand, was mentioned only in Portugal. In addition, Spain and Latvia asserted that these approaches were defined by law while Serbia and Germany claimed that neither of these approaches was usually requested. Furthermore, France highlighted the various field, political and economic constraints regarding the BACI approach, even though it's probably the most efficient method.

Regarding the field methodology used for the actual impact assessment focusing lar carnivores, camera trapping and sign surveys (especially concerning scats, tracks and kill sites) were the most reported methods, in 12 and 11 (Turkey being the exception) countries respectively. Aside from those, sign surveys focusing on scats confirmed by genetic analysis were mentioned in 8 countries (67%), direct observation in 7 countries (58%) and acoustic detection in 5 (42%). Additionally, telemetry and Abundance Index of presence signs were mentioned in 3 countries each while Capture-Recapture Index was only referenced in Italy.

For the spatial scale used for EIA focusing on large carnivore species, in 7 countries (58%) is considered "only impact area", in 6 countries (50%) is the assumed home range of large carnivores or the species distribution area, in 5 countries (42%) the impact area and close surroundings are considered while impact area and wide surroundings (more than 5km) is considered in 3 countries (25%).

Regarding the use of mitigation measures, 9 countries (75%) asserted that some type of measure is being applied for infrastructure development focusing on large carnivores, while 3 countries (25%) claimed no measures were being employed (Germany, Serbia and Latvia). However, countries where mitigation measures are being applied, there were, in general, no standard framework involved, with variations between projects being mentioned by France and Albania.

Protection of sensitive areas and wildlife passages were the most reported mitigation measures currently employed (n=8; 67%), with infrastructure decommission being the least common (n=1, 8%), as it was only mentioned in Slovenia. Furthermore, habitat improvement was mentioned in 4 countries (33%), including forest management (n=4), damage prevention (n=2), prey/food improvement (n=3) and public awareness (n=2) (Figure 30).

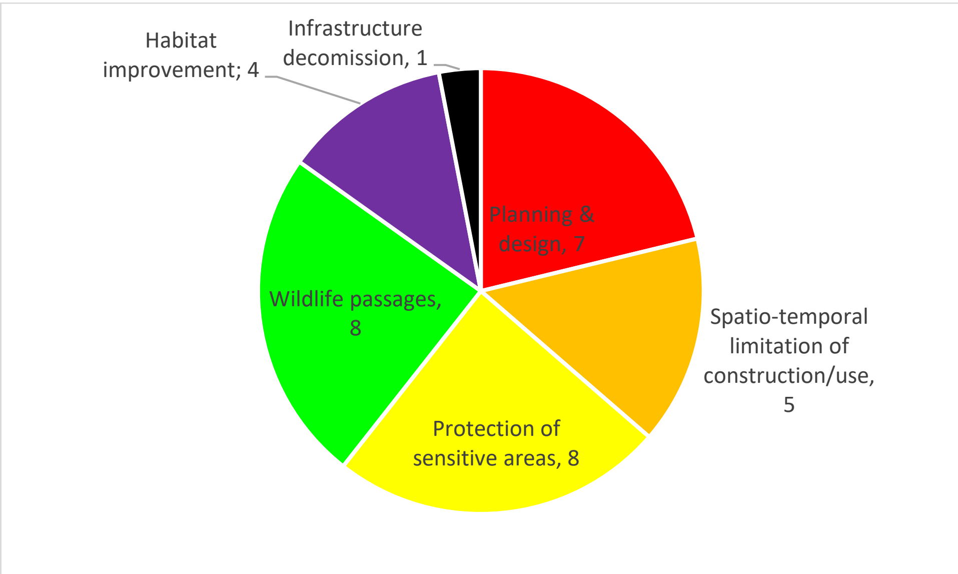

Figure 30: Number of answers in the online survey mentioning each type of mitigation measure

As for the efficiency evaluation of the mitigation measures that are being applied, 5 countries (42%) answered that there was no evaluation (Germany, Italy, Slovenia, Latvia and Serbia), 4 claimed that the results weren’t clear while the remaining 3 countries asserted that the results were positive (Spain, Romania and Turkey). Several surveyed countries mentioned the necessity to improve the evaluation of mitigation measures' efficacy in the future.

Finally, 4 countries reported that there were clear guidelines at a national level for EIA and Mitigation hierarchy focusing on large carnivores, namely Portugal, Spain, Croatia and Romania.

4. Discussion

Overall, the findings of this study reveal that the current knowledge on impacts and mitigation measures of infrastructures on large carnivores varies according to country, infrastructure types and carnivore species, highlighting the need for further research to address an increasing concern in wildlife conservation.

The literature review showed that the number of publications and conservation increased from the 1980's to the 2010's, with this trend appearing to continue in the current decade. This suggests an increased interest from researchers regarding infrastructure effects on large carnivores, as revealed for other studies addressing bibliometric analysis related to wildlife research (Bencatel et al., 2018). As urbanization expands, forcing humans and wildlife in general to live in closer proximity, the research interest regarding top predators is expected to increase in the last decades. Still, studying large carnivores is not an easy task, as evidenced by the large amount of unclear results from studies focusing on anthropogenic infrastructures on these species (Trouwborst et al., 2016; Papp et al., 2022). Another compelling note is that no reviewed publications or conservation projects were associated with countries such as Albania, Latvia, North Macedonia, Lithuania, Netherlands and Luxembourg, despite most of these being home to stable large carnivore populations or being currently recolonized by wolves (case of Netherlands and Luxembourg) (Reinhardt et al., 2023). For Albania and Latvia, some information on the topic was gathered from the online survey, although for the former country there is no clear standard framework for the application of mitigation measures pertaining to infrastructure effects on large carnivores, while Latvia reported that no mitigation measures were currently being employed at a national level.

The first working hypothesis (all infrastructure types have negative effects) was not verified, since this literature review showed that viewpoints were the only infrastructure type for which there was no report of negative responses from large carnivores. Still, viewpoints were only assessed in one single study, focusing bears (Zarzo-Arias et al., 2018), meaning that other species, or even other bear populations, might have negative responses that have been overlooked. Nevertheless, all other infrastructure types triggered negative responses from large carnivores.

For the second and third hypotheses, the modelling approach failed to detect significant variables for most species and countries. Still, for the second hypothesis (species protection status influences number of publications), it was shown that the wolf protected status is positively related to the number of publications (either in total or only reporting mitigation measures) on infrastructures focusing this species per country. This was expected since it makes sense that countries that offer a protected status to a certain species would pay more attention on infrastructure impacts and mitigation focusing this species. As for the golden jackal, the model was significant although none of the covariates explained the number of publications on these species, likely due to the low number of related publications (n=9).

For the third working hypothesis (socio-economic traits influence number of publications), the modelling approach revealed that only road network density at a national level have a positive influence in the number of publications regarding wolves. This suggests that countries with higher road density are associated with more literature on effects of infrastructures on wolves, which is expected considering the higher need to address road network as conservation concern. Regarding the number of publications mentioning mitigation measures, no significant variable was detected.

Lastly, the fourth working hypothesis (species home range influences number of publications) was not verified as no significant influence was detected between home range size of large carnivore species and the number of reviewed publications. This may be related to the low variation in this descriptor, since home range values for each large carnivore species are all considerably high.

Effects of each infrastructure type

Roads, in general, were the most common type of infrastructure reported in the scientific publications, both in Europe and North America, as well as in conservation projects, with modelling approaches suggesting a significant influence of road network density in the number of publications regarding the grey wolf. Furthermore, roads were mostly associated with negative responses for all considered large carnivore species and for several biological parameters (Passoni et al., 2017; Donatelli et al., 2022). Roadkills were the main reported effect in all large carnivore species, except for wolverine (not only pertaining to roads but also railways), suggesting that linear transport infrastructure-driven mortality is one of the main threats to large carnivores. Previous publications report that the majority of bears killed in roads were subadults, i.e. less experienced individuals that were likely dispersing (Skuban et al., 2017) and that bears were more likely to face mortality risk by crossing roads during mating season and hyperphagia

(Psaralexi et al., 2022). The exception for wolverine might be related to its low population densities and limited range in remote areas with low road network density. Aside from effects on mortality, it was also evident that linear transport infrastructures, in general, have a negative impact on the movement patterns of large carnivores, acting as barriers (Rodríguez-Freire & Crecente-Maseda, 2008). Nonetheless, there are differences between the different road types as secondary roads are reported to have less significant impacts on large carnivores than higher traffic volume roads (Jędrzejewski et al., 2005). In contrary, unpaved roads are frequently reported to have positive responses from large carnivore species, as this infrastructure type is often selected as traveling routes (Eriksen et al., 2009; Zimmermann et al., 2014; Tattoni et al., 2015). The probable reasons are that, since this type of roads have much less movement than other road types, large carnivores feel more comfortable using them as a faster alternative to rugged terrain covered with vegetation (Zimmermann et al., 2014). However, selection of unpaved roads as travel routes by large carnivores was avoided when human-caused disturbance is higher, namely during daytime and especially during holiday (Naves et al., 2001, Tattoni et al., 2015; de Gabriel-Hernando et al., 2021).

Power lines were associated with some avoidance from female bears with cubs (Desmecht, 2017). However, for power lies was also reported positive responses related to the selection of easier travel routes, regarding wolves (Gurarieet al., 2011) and bears (Desmecht, 2017), showing that large carnivores may use them as travel routes but not without some constraints concerning human avoidance. The importance of low disturbance levels is also reported for large carnivores selecting road crossing sites located near forests or grasslands, where the traffic volume is lower (Find'o et al., 2018). Additionally, it was also reported that proximity to roads influences large carnivores' selection of breeding sites as they appear to select areas further away from roads, particularly roads with higher levels of disturbance (Swenson et al., 1996; May et al., 2012). On the other hand, there were reports of large carnivores using linear transport infrastructures as foraging areas, taking advantage of spilled human food and carcasses of other animals that were victims of roadkill (Morales-González et al., 2020). For the golden jackal it is even reported that higher traffic volume did not necessarily correlate with lower foraging activities near roads, demonstrating the high adaptability of this species (Bulmer, 2015).

Urban areas were also very predominant in the reviewed publications, with most studies focusing on large carnivore occurrence in relation to this infrastructure type (Jędrzejewski et al., 2005; Niedziałkowska et al., 2006). Several publications reported that large carnivores generally avoided urban areas (May et al., 2006; Nellemann et al., 2007; Eggermann, 2009), with the major exception being the golden jackal, which was reported to occur relatively close to urban areas, suggesting important foraging sites due to high availability of anthropogenic food resources (Giannatos et al., 2005; Selimovic et al., 2021). Interestingly, jackals occurring closer to urban areas consume more ungulates than jackals living far away from humans, suggesting that this generalist carnivore is attracted to roads and urban areas by carcasses of other animals that are victims to roadkill (Tsunoda & Saito, 2020). Similarly, bears are also reported to use urban areas as foraging sites (Morales-González et al., 2020), while Eurasian lynx show tolerance to urban areas when there is prey nearby, composed by species also attracted by anthropogenic food sources (May et al., 2008; Bouyer et al., 2015). Studies reporting bear and Eurasian lynx avoidance to urban areas were much more numerous than for the golden jackal, suggesting a higher adaptability and tolerance to human disturbance for the latter species. For wolf, Iberian lynx and wolverine, responses to urban areas were more overwhelmingly negative, suggesting lower tolerance to human disturbance. Nevertheless, the fact that some species can adapt by searching for food inside or near urban areas is not necessarily a good indication for the survival of these species, as consuming human-related garbage may increase risk of pathogen infection and spreading of diseases (Morales-González et al., 2020). Furthermore, dependence on anthropogenic food sources can also result in scenarios of ecological traps (Morales-González et al., 2020) where large carnivores, attracted by human-related food, use urban areas, which have low habitat suitability, higher levels of disturbance and higher risk of human-caused mortality (Steyaert et al., 2016). Despite the large amount of scientific publications focusing on urban areas and the several potential problems associated with this infrastructure type, there are very few conservation projects addressing them, especially considering how dense and widespread urban areas are. This may be a result of humans having conservation concerns regarding large carnivores, although not being as opened to compromise for these species' conservation as it pertains residential areas.

Fences were one of the infrastructures reported in scientific literature that had higher uncertainty regarding effects on large carnivores. Fences have been used to prevent carnivore attacks on livestock but there is an apparent lack of information relating to how this type of infrastructure may affect the behavior of large carnivores. There were reports of higher number of roadkills in fenced highways compared to highways without fences (Colino-Rabal et al., 2011), suggesting that fencing highways might not be an effective mitigation measure. However, there are also reports of large carnivores crossing fences with no major problems (Kowalczyk et al., 2012) and even a case in which it appeared that wolves were pushing prey towards fences in order to constrain them, improving their hunting efficiency (Del Frate et al., 2023). Still, there are publications reporting that fences act as barriers to ungulates movements as well as reporting ungulates dying after getting stuck in fences (Trouwborst et al., 2016). This may reflect that the same outcomes could potentially be verified in large carnivores, particularly for long border fences (Trouwborst et al., 2016). However, no study has properly evaluated the barrier effect of fences as well as the scale at which fences can actually impact large carnivores.

Wind farms are reported to be avoided by wolves, especially during construction phase, as individuals changed the location of their dens to areas farther away from this infrastructure type (Ferrão da Costa et al., 2018). In other cases, wolves maintained their dens near wind farms during construction phase but in turn their reproductive rate decreased and, after wind farms were in full operation, packs selected breeding sites located progressively farther from these infrastructures (Helldin et al., 2017). This can be interpreted as evidence of the influence of human presence, since the negative effects of wind farms seem to increase when there is more direct disturbance (e.g. during construction phase). As for hydropower complex, it was reported that bears appear to have considerably changed their dispersing routes to avoid this infrastructure (Delayat et al., 2019) while another report asserted that by reducing water flow, a hydropower complex was affecting aquatic and semi-aquatic populations and, consequently, higher trophic levels of the food chain, with the resident Eurasian lynx population being expected to decline as a result (Dejeu et al., 2022). It should be noted that few publications were found on these two types of infrastructures and these were only focused on one single country. Publications on wind farms were mostly related to Portugal while all publications on hydropower complex were developed in Romania, showing that interest to study these infrastructures regarding their effect on large carnivores has been slowly increasing but, so far, remains focused on specific case studies. On the other hand, no publications were found regarding solar power plants, despite being expected as an increasingly common infrastructure. As such, it is evident that more studies on effects of infrastructures associated with renewable energy is needed in the future.

Tourism-related infrastructures such as resorts, recreational cabins and viewpoints were not very prominent in the reviewed literature either. Still, there was documented avoidance from wolverines, bears and Eurasian lynx regarding cabins (May et al., 2006; Sahlén et al., 2011; Hočevar et al., 2021) and from bears in relation to recreational resorts (Nellemann et al., 2007). On the other hand, the sole publication addressing viewpoints showed that bears' feeding and nursing behavior increased with closer proximity to this infrastructure type (Zarzo-Arias et al., 2018), likely because it offers a vantage point from which bears can surveil their surroundings more efficiently compared to areas with dense vegetation. Another underrepresented type of infrastructure on the reviewed publications focusing in Europe was mines. Considering that bears are reported to avoid areas with mining activity (Trouwborst, 2016), more research should be conducted to address the effects of this infrastructure given the expected increase of open-pit mines for lithium extraction in Europe (Graham et al., 2021).

Overall, the literature review focusing infrastructure effects on large carnivores in Europe revealed that especially the brown bear, but also the grey wolf and, with less expression, the Eurasian lynx, have been the target species of more scientific studies and conservation projects, in relation to diverse types of infrastructures. This pattern may reflect the range extension of each species, since wolves and bears are present in more countries than the Iberian lynx or the wolverine. In the case of the Iberian lynx, it is apparent that there is a higher proportion of conservation programs focusing on this species in comparison to scientific studies, likely steaming from the high risk of extinction that this species faced. Concerning the golden jackal, it was expected that it would not be as commonly featured in publications as wolves and bears since jackals currently occur in less countries and show a high adaptation to human disturbance (Giannatos et al., 2005). Still, the current population expansion by this canid (Lanszki et al., 2018) leads to believe that interest on studying the effects of infrastructures on golden jackals might rise in the future.

Where and how are mitigation measures applied?

Regarding the use of mitigation measures, a lack of focus on this aspect was evident in many scientific publications. Still, for the studies that recommended mitigation measures, most were related to planning and design of infrastructures, for all infrastructure types in general (Trouwborst et al., 2016; Dennehy et al., 2021). This way, there seems to be a focus on preventing impacts rather than reversing them. The contrary was observed for conservation projects, which focused more on indirect habitat improvement, especially through public awareness campaigns. This was expected since the success of conservation programs rely highly upon the involvement of stakeholders, whether for funding purposes, manpower or simply being open to accept certain compromises in favor of helping the conservation of a large carnivore. Although some reviewed publications highlighting the importance of public awareness (e.g. Bartón et al., 2019; Kudrenko et al., 2021), it was not as evident compared to conservation programs, demonstrating a disconnect between the focus of scientific studies and conservation actions. Improvement of prey availability was also mentioned as a part of indirect habitat improvement, particularly on conservation projects, although less commonly than public awareness (LIFE97 NAT/GR/004249; LIFE13 NAT/RO/000205). Furthermore, mitigation measures related to protection of sensitive areas and spatio-temporal limitation of infrastructure construction/use, which were mostly associated with urban areas and roads in the literature review, were absent from the reviewed conservation projects, likely because most programs look to act on already existing problems rather than preventing future impacts. This might also be the reason why measures associated with planning and design were not as common in conservation programs. On the other hand, the reviewed scientific publications and conservation programs were in agreement pertaining to wildlife passages, as this type of mitigation was considerably mentioned in both cases, specifically when pertaining to linear transport infrastructures (Kaczensky et al., 2003). Additionally, infrastructure decommission was the type of mitigation measure less emntioed in both scientific publications and conservation projects, which was also anticipated considering the economic and policy-related problems associated with removing an infrastructure (Doyle & Havlick, 2009). In general, infrastructure decommissioning was recommended mostly for roads (Kusak et al., 2000; Kudrenko et al., 2021; LIFE02 NAT/EE/008555). Another type of mitigation measure that was underrepresented in the scientific publications and conservation programs was direct habitat improvement. While indirect habitat improvement, as previously stated, was highly mentioned in the conservation programs, direct habitat improvement received considerably less attention, despite some reviewed publications and conservation programs highlighting the importance of forest management in the conservation of large carnivores (Desmech, 2017; Ferrão da Costa et al., 2018; LIFE20 NAT/NL/001107). The few mentions of this mitigation measure type was unexpected, considering that it would bring direct benefits to the entire ecosystem, affecting the entire trophic web in a positive way (Franklin et al., 2018).

The proportion of reviewed publications recommending mitigation measures was higher for the wolverine and the Iberian lynx than the other large carnivore species, in spite of both species being associated with less publications and having a limited range (Kaczensky et al., 2013). This suggests that studies on these species might be fewer but cover more aspects regarding their conservation, likely because their populations are smaller and, as such, are currently in a more precarious position. This trend can also be seen in the case of wolves and wind farms. Reviewed publications addressing wind farms were focused on wolves and in Portugal, which has a small and endangered wolf subpopulation, located south of Douro river (Ferrão da Costa et al., 2018). Despite this, every publication on wind farms recommended mitigation measures, supporting the idea that when populations are smaller, the research focusing on them aims to address more details.

There were several specific mitigation measures that were absent from the reviewed case studies that are already being currently employed or tested for efficiency, particularly pertaining to roads and wildlife-vehicle collisions. This included Roadside Animal Detection System (RADS), which has been shown to help reduce vehicle speed in USA (Grace et al., 2017), virtual fences, that appear to have the potential of reducing wildlife-vehicle collisions albeit more studies on its efficiency are necessary (Stannard et al., 2021) and use of odor repellents, which was evaluated in Czechia although not for large carnivore species (Bíl et al., 2018).

Comparing the reviewed publications regarding infrastructure effects on large carnivores focusing in Europe to case studies in North America reinforced the idea that large carnivore species with wider distribution were associated with more literature, as grey wolves and grizzly bears were far more reported than wolverines, in both continents. Roads, in general, were the more frequently addressed infrastructure in North America as well, reinforcing the negative effects that this infrastructure type has on large carnivores, especially highways (Waller & Servheen, 2010, Northrup et al., 2012). On the other hand, urban areas were substantially less common in the reviewed publications from North

America, although reporting similar effects to the ones documented in Europe were also demonstrated, namely bears being attracted to anthropogenic food sources and, consequently, the potential that urban areas have as ecological traps (Lamb et al., 2017).

Mines received more attention on the reviewed literature from North America compared to Europe, albeit with low expression. Most reviewed publications reported negative impacts on large carnivores, asserting that wolves would go near coal mines infrequently (Williamson-Ehlers, 2012) while bears avoided active mines (Cristescu et al., 2011). Additionally, it was also reported that bears would select inative mines as foraging sites, demonstrating that decommissioning of this type of infrastructure can have positive effects on large carnivore species (Cristescu et al., 2011). Furthermore, the North American literature reported pipelines, which was an infrastructure type not mentioned in the reviewed publications focusing Europe. Regarding this infrastructure, it was reported that although wolves would, in some cases, avoid them when pipeline density was high (Williamson-Ehlers, 2012), they would also often select them as travel routes, particularly during winter, to increase their travelling speed (Dickie et al., 2017). It was also reported that woodland caribous (*Rangifer tarandus caribou*), a main prey of grey wolves in North America, avoid pipelines (Williamson-Ehlers, 2012), suggesting that while large carnivores may use infrastructures such as unpaved roads, power lines and pipelines as easier travel routes that allow faster travelling speed than rugged terrain with dense vegetation, their prey actually avoid these linear infrastructures in favor of areas with denser vegetation, likely to avoid large carnivore presence. Moreover, it is important to note that infrastructures related to renewable energy production (wind farms, solar power plants ad hydropower complex) were absent from the reviewed publications focusing North America, strengthening the argument that more information is necessary regarding the effects that these types of infrastructure have on large carnivore species.

Mitigation measures were actually more commonly reported in North American studies than in Europe, even though several publications did not recommend any measures either. Most of the recommended mitigation in North America were associated with planning and design, similarly to Europe (Sawaya et al., 2019). Wildlife passages, as expected, were also mainly related to linear transport infrastructures, specifically highways, with one study adding that balloon sections in highways (i.e. areas where the median strip is widened to include substantial amounts of natural habitat) were selected by wolves as crossing sites since they allow higher visibility (Kohn et al., 2009).

Infrastructure decommission was the least common type of mitigation measure proposed in North American publications, and was particularly associated with roads (Lamb et al., 2018), similarly to Europe. Direct habitat improvement was also less documented and mostly related to roads (Scrafford et al., 2018).

The online questionnaire sent to large carnivore experts revealed that several countries are missing clear guidelines and frameworks for both EIA and mitigation measure application. It was reported, for most countries, that protected species as well as protected areas had major influence on the decision-making process for conducting an EIA. This raises concerns regarding the conservation of large carnivore populations that are not protected at a national level or occur in unprotected areas. Some countries, such as Portugal and Spain, asserted that EIA are conducted for any infrastructure development project taking place inside the known range of a large carnivore population, however this does not seem to be the standard. It was also noticeable that roads were, once again, the most commonly mentioned infrastructure while wind farms, power lines, tourism-related infrastructures and mines receiving more mentions than expected, considering their reduced prominence in the reviewed publications. This suggests that lack of focus on certain infrastructures in scientific publications does not necessarily relate to the effects of those same infrastructures on large carnivores being underappreciated by the policies of each country regarding EIA and employment of mitigation measures.

Most countries agreed that camera trappings and sign surveys were the best field methods to use during an EIA, with the BACI approach being mentioned as the most efficient and common method for post-monitoring. Regardless, the fact that Serbia and Germany claimed that post-monitoring approaches were not usually requested while France highlighted the existence of political, economic and field constraints pertaining to the application of the BACI approach demonstrates that there is not a real consensus regarding how an EIA should actually be conducted in Europe.

Mitigation measures associated with protection of sensitive areas for large carnivores was more common in the answers to the online survey than in the reviewed literature. This focus on certain areas was reinforced when most countries reported that EIA focusing on large carnivores include only the impact area, with a number of countries also including close surroundings or the assumed home range of large carnivores. The fact that few countries asserted that EIA includes the impact area and wide surroundings demonstrates that, in most countries, large carnivore conservation is mainly focused on certain areas deemed relevant, underappreciating the impacts that infrastructure development might have on areas that are not protected or located near the impact area. Including larger areas in evaluation and mitigation procedures regarding infrastructure development could increase efficiency but it would also come with social, political and economic problems. As such, more studies to evaluate the optimal scale for EIA targeting large carnivores are recommended.

Wildlife passages were often mentioned in the online survey, proving the relevance that this type of mitigation has, especially regarding linear transport infrastructures. Planning and design was mentioned by most countries, also reinforcing the importance currently given to preventing negative effects from the beginning. On opposite side, the aforementioned problems of infrastructure decommission were once more highlighted by the lack of references for this mitigation type from most countries. Habitat improvement-related actions remained fairly uncommon as a mitigation measures applied in European countries, although for most cases where it is being applied it does include forest management.

The proper evaluation of mitigation measures efficiency was absent from the majority of reviewed publications as well as from the countries that answered the online questionnaire. Furthermore, most countries reported that there were currently no clear guidelines at national level for EIA and mitigation hierarchy application focusing on anthropogenic infrastructure effects on large carnivores, rendering the need for more applied research and technical support on this relevant topic for wildlife conservation.

5. Conclusions and future research

This study provides valuable insights regarding effects of infrastructures on large carnivores, based on a descriptive approach of results obtained by literature review and online questionnaire survey. The main finding was that large carnivore species occurring in Europe have mostly negative responses to several infrastructure types. Furthermore, it also showed that there is the need for improvement pertaining to the current knowledge on mitigation measures to counter these effects. However, it was demonstrated that the majority of infrastructures can and have produced negative impacts on large carnivores, although there are some that have produced positive responses. Protection status of large carnivore species and road network density at a national level were the main determinants related to the number of scientific publications regarding this topic.

The analysis described in this study is associated with some methodological constraints, namely, difficulties with finding available literature as, certainly, publications pertaining to this topic were not detected due to a limited or difficult access. There were also limitations to the modelling approach, due to small sample sizes for certain species or lack of variation in some selected variables, which prevented significant statistical power. Furthermore, there were only 12 responses to the online questionnaire sent to large carnivore experts, reflecting a low response rate (33%), considering the 36 different nationalities represented in LCIE, which limited the conclusions taken from this survey.

This review highlighted the need for future research, especially regarding certain types of infrastructures (e.g. related to renewable energy production) and large carnivore species (e.g. wolverine and Iberian lynx) that were poorly addressed in the reviewed publications, as well as a better evaluation of the efficiency of different mitigation measures (e.g. RADS, virtual fences, ballooned sections in highways). Additionally, defining clear guidelines for EIA and mitigation procedures in relation to infrastructure effects on large carnivores, at both national and Pan-European levels, is highly recommended. Finally, a larger focus on offset mitigation measures, such as habitat improvement and damage compensation is recommended to assure a sustainable coexistence between the expanding populations of large carnivores and the expected increase in infrastructure development.

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Figure Credits

Figure 1 – taken from: https://as2.ftcdn.net/v2/jpg/02/50/58/65/1000_F_250586522_uzqYp3hqIdCaqkY8pDsWS6VlC1QN025k.jpg;

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Figure 3 – taken from:
https://www.aboutanimals.com/images/eurasian-lynx-og.jpg;

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Figure 4 – taken from:
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Figure 8 – taken from:
https://www.benvenutolimos.com/blog/wp-content/uploads/2019/08/87911990_s.jpg (roads);
https://d25jl7n04nddev.cloudfront.net/blog/images/2459-b2cfa2f57b8e8e820da426faea655d07.jpg?1582215071 (urban areas);
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7. Annexes

Annex S1: List of reviewed literature regarding effects of infrastructures on large carnivores

Scientific publications in Europe:

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ConnectGREEN - Restoring and managing ecological corridors in mountains as the green infrastructure in the Danube basin (Interreg)
LIFE94 NAT/P/001055 - Conservation of the Wolf in Portugal
LIFE94 NAT/P/001058 - Conservation of the Iberian Lynx
LIFE97 NAT/GR/004249 - Conservation of *Canis lupus* and its habitats in Central Greece (Canis lupus)
LIFE99 NAT/IT/006237 - Restoration of grassland habitats in the Monte Gemelli, Monte Guffone SIC (Monte Guffone).
LIFE02 NAT/FIN/008469 - Protection of aapa mire wilderness in Ostrobothnia and Kainuu (Olvassuo)
LIFE02 NAT/EE/008555 - Protection of priority forest habitat types in Estonia (EE Priority Forests)
LIFE02 TCY/CRO/014 - Conservation and management of wolves in Croatia (CROWOLFCON)
LIFE07 NAT/GR/000291 - Demonstration of Conservation Actions for *Ursus arctos** and habitat type 9530* in Northern Pindos N.P., Grevena Prefecture, Greece (PINDOS/GREVENA)
LIFE10 NAT/ES/000570 - Recovering the historic distribution range of the Iberian lynx (*Lynx pardinus*) in Spain and Portugal (Iberlince)
LIFE11 BIO/IT/000072 - Demonstration of a system for the management and reduction of collisions between vehicles and wildlife (LIFE STRADE)
LIFE12 NAT/ES/000192 - Habitat defragmentation for brown bear in the Cantabrian mountains (LIFE BEAR DEFRAGMENTATION)
LIFE13 NAT/RO/000205 - Implement best practices for in-situ conservation of the species *Canis lupus* in the Eastern Carpathians (WOLFLIFE)
LIFE13 NAT/SI/000550 - Population level management and conservation of brown bears in northern Dinaric Mountains and the Alp (LIFE DINALP BEAR)
LIFE15 NAT/GR/001108 - Improving Human-Bear Coexistence Conditions in Municipality of Amyntaio (LIFE AMYBEAR)
LIFE17 NAT/IT/000464 - Preventing Animal-Vehicle Collisions – Demonstration of Best Practices targeting priority species in SE Europe (LIFE SAFE-CROSSING)
LIFE18 NAT/GR/000768 - Improving human-bear coexistence in 4 National Parks of South Europe (LIFE ARCPROM)
LIFE18 NAT/IT/000972 - Coordinated actions to improve wolf-human coexistence at the alpine population level (LIFE WOLFALPS EU)
LIFE19 NAT/ES/001055 - Creating a genetically and demographically functional Iberian Lynx (*Lynx pardinus*) metapopulation (LIFE LYNXCONNECT)
LIFE20 NAT/NL/001107 - Enhancing the viability of Brown Bears in Central Italy and Greece through the development of coexistence corridors (LIFE Bear-Smart Corridors).
LIFE21-NAT-IT-LIFE WILD WOLF/101074417 - Concrete actions for maintaining wolves wild in anthropogenic landscapes of Europe (LIFE WILD WOLF)

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Annex S2: Content of the online questionnaire sent to experts on large carnivores

Large Carnivore Initiative for Europe
IUCN/SSC SPECIALIST GROUP

SSC IUCN

ONLINE QUESTIONNAIRE ON IMPACT EVALUATION TARGETING LARGE CARNIVORES

In the scope of the Large Carnivore Initiative for Europe (LCIE) WG 4-IV "Impact of Infrastructure Development on Large Carnivores", we have developed a short questionnaire survey to conduct a country-level analysis on the procedures related to the assessment, mitigation and compensation of infrastructure impacts targeting large carnivores in Europe. We invite all LCIE member and/or other experts to contribute to this survey, preferably until June 15. More than one contributor per country is accepted. The survey includes 17 questions and will take, approximately, 20 minutes to answer.

This work is conducted by Bruno Miguel, a Master's degree student, under the supervision of Francisco Álvares (BIOPOLIS-CIBIO/InBIO, University of Porto) and Paulo Gama Mota (University of Coimbra). Any questions or suggestions about the survey can be sent to the following e-mails: brunorafamiguel@gmail.com and falvares@cibio.up.pt

Thank you in advance for your contribution!

E-mail *

Texto de resposta curta

Name: *

Texto de resposta curta

Country: *

Texto de resposta curta

Job position: *

Texto de resposta curta

Institution: *

Texto de resposta curta

Does Environmental Impact Assessment (EIA) for infraestruture development in your country usually takes in consideration Large Carnivores (LC)? *

- Yes
- No

If yes, please detail the requirements/determinants for EIA on LC at national level (e.g. depending on infrastructure size or type, all LC range, only inside protected areas) and the respective legal framework (please provide link, if available):

Texto de resposta longa

Which target species (for EIA)? *

- [ ] Grey Wolf

- [ ] Brown Bear

- [ ] Eurasian Lynx

- [ ] Iberian Lynx

- [ ] Wolverine

- [ ] Golden Jackal

For which infrastructure(s) type (for EIA)? *

- [ ] Roads
- [ ] Railways
- [ ] Fences
- [ ] Wind farms
- [ ] Mines
- [ ] Power lines
- [ ] Urban areas
- [ ] Tourism: Resorts, Recreational cabins, Golf courses...
- [ ] Outra opção...

What factors have more influence in deciding that an EIA considering LC is necessary? *

- [ ] Location and size of the infrastructure, regardless of LC status
- [ ] The target LC species has a protected status, at a national level
- [ ] The target LC species has low population size, at regional level
- [ ] It's a common procedure for all infrastuctures and wildlife species
- [ ] Outra opção...

During post-EIA monitoring, which approach is used for Impact assessment on LC? *

- [ ] Exclusion effect
- [ ] Before-After Control-Impact (BACI)
- [ ] Cumulative effects
- [ ] Outra opção...

Which biological trait is assessed for impact assessment on LC? *

- [ ] Occurrence
- [ ] Habitat selection (including resting and breeding sites)
- [ ] Habitat selection (only including land cover categories)
- [ ] Movement
- [ ] Reproduction
- [ ] Mortality
- [ ] Physiology (i.e. stress)
- [ ] Extinction risk (i.e. genetic diversity)
- [ ] Outra opção...

Please detail below if different traits are assessed for each Infrastructure type: *

Texto de resposta longa

Which methodology is used for Impact Assessment on LC? *

- [ ] Telemetry
- [ ] Sign survey (including scats, trails, kill sites and other evidences)
- [ ] Sign survey based on scats confirmed by genetic analysis
- [ ] Camera-trapping
- [ ] Direct observation (alive/dead)
- [ ] Acoustic detection
- [ ] Abundance Index of presence signs
- [ ] Capture-Recapture Index
- [ ] Outra opção...

Please detail below if different methods are assessed for each Infrastructure type: *

Texto de resposta longa

Which spatial scale is used for Impact assessment on LC? *

- [ ] Only Impact area (project area of a given infrastructure)
- [ ] Impact area and close surroundings (up to 5km)
- [ ] Impact area and wide surroundings (more than 5km)
- [ ] Assumed home range of existing LC
- [ ] Outra opção...

Please detail below if different scales are assessed for each infrastructure type: *

Texto de resposta longa

Are Mitigation Measures applied for infrastructure development on LC? *

- ( ) Yes
- ( ) No

If yes, please detail the legal framework and requirements at national level:

Texto de resposta longa

Which Mitigation Measures are considered for Impact assessment on LC? *

- [ ] None
- [ ] Planning & design
- [ ] Spatio-temporal limitation of construction period/infrastructure use
- [ ] Protection of sensitive areas
- [ ] Wildlife passages
- [ ] Off-set habitat improvement
- [ ] Infrastructure decomission
- [ ] Outra opção...

Please detail below if different methods are assessed for each Infrastructure type: *

Texto de resposta longa

If you selected the "Off-set habitat improvement" option, specify what type:

- [ ] Forest management
- [ ] Prey improvement
- [ ] Damage prevention
- [ ] Public awareness
- [ ] Outra opção...

Did the Mitigation Measures provide positive results? *

- ( ) Yes
- ( ) No
- ( ) Not clear
- ( ) There was no evaluation

Specify other relevant information regarding the previous question, if necessary:

Texto de resposta longa

Are there clear official guidelines for EIA and Mitigation hierarchy targeting LC in your country? *

- ( ) Yes
- ( ) No

Please provide additional comments or information:

Texto de resposta longa

Annex S3: Information on the respondents of the online questionnaire sent to experts on large carnivores

Table S14: Name, country, job position and institution of the respondents to the online questionnaire

Expert name	Country	Job position	Institution
Aleksander Trajce	Albania	Director	Protection and Preservation of Natural Environment in Albania (PPNEA)
Djuro Huber	Croatia	Professor emeritus	Faculty for Veterinary Medicine of Zagreb
Victoria Platini	France	Student engineer in road ecology	Cerema; Parc Naturel Régional du Haut-Jura
Ilka Reinhardt	Germany	Researcher	LUPUS - Germany Institute for Wolf Monitoring & Research
Francesca Marucco	Italy	Professor	University of Torino
Jānis Ozoliņš	Latvia	Senior researcher	Latvian State Forest Research Institute (SILAVA)
Gonçalo Ferrão da Costa	Portugal	Senior consultant	Bioinsight & Ecoa
Ovidiu Ionescu	Romania	Wildlife researcher and professor	University of Transilvania
Duško Ćirović	Serbia	Associated professor	University of Belgrade
Klemen Jerina	Slovenia	Professor	University of Ljubljana
Juan Carlos Blanco	Spain	Large carnivore biologist	Consultores en Biologia de la Conservación SL
Deniz Mengüllüoğlu	Turkey	Freelance ecologist	N/A

Annex S4: Detailed results from modelling procedures

Table S15: Significance of the test of the number of publications on wolves per country as determined by protection status, forest cover percentage, road network density and wolf population size using a Generalized Linear Model

Omnibus Test[a]

Likelihood Ratio Chi-Square	df	Sig.
12.782	5	.026

Dependent Variable: Wolf publications
Model: (Intercept), Wolf status, Forest cover percentage, Road network density, Wolf pop

Table S16: Parameter estimates of the test of the number of publications on wolves per country as determined by protection status, forest cover percentage, road network density and wolf population size using a Generalized Linear Model

Parameter Estimates

Parameter	B	Std. Error	95% Wald Confidence Interval Lower	95% Wald Confidence Interval Upper	Hypothesis Test Wald Chi-Square
(Intercept)	.970	.6437	-.292	2.232	2.271
[Wolf status=]	-1.469	.6881	-2.817	-.120	4.556
[Wolf status=not protected]	-1.393	.4539	-2.283	-.504	9.422
[Wolf status=protected]	0[a]	.	.	.	.
Forest cover percentage	.018	.0122	-.006	.042	2.150
Road network density	-.557	.2585	-1.063	-.050	4.636
Wolf pop	.000	.0001	-5.859E-5	.001	2.448
(Scale)	.431[b]	.1246	.245	.760	

Table S17: Significance of the test of the number of publications on jackals per country as determined by protection status, forest cover percentage, road network density and jackal population size using a Generalized Linear Model

Omnibus Test[a]

Likelihood Ratio Chi-Square	df	Sig.
11.206	4	.024

Dependent Variable: Jackal publications
Model: (Intercept), Jackal status, Forest cover percentage, Road network density

Table S18: Parameter estimates of the test of the number of publications on golden jackals per country as determined by protection status, forest cover percentage, road network density and jackal population size using a Generalized Linear Model

Parameter Estimates

Parameter	B	Std. Error	95% Wald Confidence Interval Lower	95% Wald Confidence Interval Upper	Hypothesis Test Wald Chi-Square
(Intercept)	.823	.4284	-.017	1.662	3.689
[Jackal status=]	-.282	.2990	-.868	.304	.886
[Jackal status=not protected]	-.422	.2544	-.921	.076	2.754
[Jackal status=protected]	0[a]	.	.	.	.
Forest cover percentage	-.012	.0084	-.029	.004	2.134
Road network density	.306	.1596	-.007	.619	3.672
(Scale)	.053[b]	.0250	.021	.133	

Table S19: Significance of the test of the number of publications on bears per country as determined by forest cover percentage, road network density and bear population size using a Generalized Linear Model

Omnibus Test[a]

Likelihood Ratio Chi-Square	df	Sig.
5.563	3	.135

Dependent Variable: Bear publications
Model: (Intercept), Forest cover percentage, Road network density, Bear pop
a

a. Compares the fitted model against the intercept-only model.

Table S20: Significance of the test of the number of publications on Eurasian lynx per country as determined by protection status, forest cover percentage, road network density and Eurasian lynx population size using a Generalized Linear Model

Omnibus Test[a]

Likelihood Ratio Chi-Square	df	Sig.
5.100	3	.165

Dependent Variable: E. Lynx publications
Model: (Intercept), Forest cover percentage, Road network density, E- lynx pop
a

Table S21: Significance of the test of the number of publications mentioning mitigation measures per country as determined by protection status, forest cover percentage, road network density and wolf population size using a Generalized Linear Model

Omnibus Test[a]

Likelihood Ratio Chi-Square	df	Sig.
11.806	5	.038

Dependent Variable: Mitigation measures
Model: (Intercept), Wolf status, Forest cover percentage, Road network density, Wolf pop

Table S22: Parameter estimates of the test of the number of publications mentioning mitigation measures per country as determined by protection status, forest cover percentage, road network density and wolf population size using a Generalized Linear Model

Parameter Estimates

Parameter	B	Std. Error	95% Wald Confidence Interval		Hypothesis Test
			Lower	Upper	Wald Chi-Square
(Intercept)	1.222	.5688	.107	2.337	4.612
[Wolf status=]	-1.522	.6008	-2.699	-.344	6.414
[Wolf status=not protected]	-1.030	.3718	-1.759	-.302	7.678
[Wolf status=protected]	0[a]	.	.	.	.
Forest cover percentage	.009	.0107	-.012	.030	.692
Road network density	-.420	.2237	-.858	.019	3.521
Wolf pop	.000	.0002	-3.760E-5	.001	2.971
(Scale)	.326[b]	.0956	.183	.579	

Table S23: Significance of the test of the number of publications mentioning mitigation measures per country as determined by protection status, forest cover percentage, road network density and bear population size using a Generalized Linear Model

Omnibus Test[a]

Likelihood Ratio Chi-Square	df	Sig.
2.220	4	.695

Dependent Variable: Mitigation measures
Model: (Intercept), Bear status, Forest cover percentage, Road network density, Bear pop
a

a. Compares the fitted model against the intercept-only model.

Table S24: Significance of the test of the number of publications mentioning mitigation measures per country as determined by protection status, forest cover percentage, road network density and Eurasian lynx population size using a Generalized Linear Model

Omnibus Test[a]

Likelihood Ratio Chi-Square	df	Sig.
4.330	5	.503

Dependent Variable: Mitigation measures
Model: (Intercept), Forest cover percentage, Road network density, E. Lynx status, E- lynx pop
a

a. Compares the fitted model against the intercept-only model.

Table S25: Significance of the test of the number of publications mentioning mitigation measures per country as determined by protection status, forest cover percentage, road network density and golden jackal population size using a Generalized Linear Model

Omnibus Test[a]

Likelihood Ratio Chi-Square	df	Sig.
5.766	5	.330

Dependent Variable: Mitigation measures
Model: (Intercept), Jackal status, Jackal pop, Forest cover percentage, Road network density[a]

a. Compares the fitted model against the intercept-only model.