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Prioritizing road sections for wildlife fencing to reduce road mortality

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Contribution of Authors

As first author, I was responsible for the conception, design, data analysis and the writing of the thesis and the manuscript related to this thesis. The manuscript was co-authored by Dr. Jochen Jaeger, who advised on experimental design, editing, and overall revisions to the manuscript. The thesis was supervised by Dr. Marco Bassani, who advised on the experimental design, editing and overall revision to the thesis.

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1. Introduction

Transportation infrastructures are fundamental to economic and social development. Since ancient times, advances in network infrastructures have always fueled waves of globalization. An efficient transportation network provides economic and social opportunities and benefits that result in positive multipliers effects such as better accessibility to markets, employment and additional investments. The emerging economies among the world, now more than ever, are drawing up ambitious plans to further increase the capacity of their transportation networks and promote regional and intercontinental trade flow of materials.

However, the uncontrolled spread of the infrastructures brings along huge changes in the landscapes drastically jeopardizing the biodiversity of the affected natural areas. Besides the direct habitat loss due to the road itself, the construction of road infrastructures in wilderness areas inevitably severs complex webs of nature connectedness, fragmentizing the habitat, acting as a barrier to movement for the animals and enhancing mortality due to collisions with vehicles. Having an understanding on such effects is important as it can help in formulating a more compelling conservation goal that benefits both human and nature.

The interaction of road and natural areas presents, besides the numerous environmental problems, also an urgent risk factor.

Wildlife-vehicle collisions in fact can have negative consequences for both people and animal, and though human fatalities are relatively rare, roughly 4–10 percent of reported WVCs involving large animals result in injuries to drivers and their passengers.

Transportation strategies can be used not only to avoid unexpected scenarios but also to determine the magnitude of the issues. WVC result in enormous property damage losses for vehicle owners and insurers, and some cost-benefit analysis demonstrated that, in some areas, the total costs associated with animals-vehicle collisions could be even greater than the costs associated with implementing mitigation measures aimed at keeping these animals from accessing the highway and providing safe crossing opportunities (Huijser et al. 2009). Nonetheless, very few cost-benefit analyses exist and although this may seem surprising, wildlife-vehicle collisions, at least until recently, are not always included in safety analyses by transportation agencies. Greater awareness of the problem would bring to cost-effective mitigation measures that would reduce the number of injuries and fatalities to drivers and passengers while minimizing the impact of the road. Techniques designed to lessen the number of wildlife-vehicle collisions have been used for decades and are a necessary component of a sustainable transportation strategy.

The most implemented are wildlife warning signs, animal detection systems, wildlife reflectors, olfactory repellents, ultrasonic warning whistles, habitat alteration, public awareness programs, changes in road-verge management, wildlife fences, wildlife crosswalks, and wildlife crossing structures (Iuell et al. 2003; Clevenger and Ford 2010; Huijser and McGowen 2010).

Among these, many researchers agree that the most effective and robust way to reduce accidents is the combination of wildlife fencing and wildlife crossing structures (Huijser et al. 2009). The combined use of these two measures, in fact, would not only reduce road mortality, preventing animal's access to the road but would also diminish the risk of local population extinction due to population isolation, since many of the animals within the fence would be funneled to safe crossing passages. Wildlife-vehicle collisions are not random occurrences but are spatially clustered, and identifying the areas with the highest rate of wildlife crossings would consent to prioritize the sections in which the fence is more needed and increase the efficiency of the mitigation measure.

Many studies recognize these areas grouping variables such as land use, wildlife habitat, and terrain into multivariate models. WVC models are advantageous because they can predict likely roadkill patterns and the need for mitigation planning on roads without road mortality surveys, and implement mitigation measures in advance.

Other studies recognize these areas analyzing the spatial pattern of wildlife-vehicle collision. Road mortality surveys are always advisable since modeling the spatial pattern of the roadkill it is possible to implement more efficient mitigation measures. There are different methods for analyzing spatial patterns and detecting hotspots including spatial autocorrelation and cluster analysis. The most used techniques used to identify non-random cluster of WVCs along roads are (a) linear nearest neighbor analysis, (b) Ripley k analysis, (c) Density measures WVCs per mile segment, (d) Hotspot Identification Analysis.

However, even with the knowledge of the spatial pattern of the wildlife-vehicle collision, the identification of locations and type of mitigation measures is often a challenge for road planners and ecologists. Since animals that approach the fence may decide to walk until his end and sidestep it, the fence shouldn't be limited to the sections with the highest density of animals' crossing identified by the WVC analysis, but should be continued beyond these stretches to prevent fence end effects, i.e. elevated road-kill immediately adjacent to fence ends.

Furthermore, the mitigation measure implemented change by varying the scale (or bandwidth) with whom the spatial configuration of roadkill is analyzed. An efficient configuration of fence can be implemented only if the result of the spatial composition of roadkill are crossed with considerations on the home ranges of the animals in the analysis. While a scale too fine would create many sections of fence that could be inefficient due to a high probability of fence-end effect, a too coarse-scale would result in the implementation of fences parts of which would not be needed. Spanowicz et al. called this trade-off the FLOMS trade-off: Few large or many short fences?

The ideal intervention is the configuration of fence with stretches that are not so long to waste fencing where there are few animal fatalities, and not so small to be easily sidestepped. Various handbooks offer suitable specifications about how and where the fence should be built. However, it is still unclear where fences should start and end, how long the sections should be prolonged to prevent the fence end effect, and if the implementation of few long sections of fence presents greater benefit than the implementation of many short sections.

To discuss the fence-end effect and the FLOMS trade-off, we evaluated a stretch of 68.5km of Highway 175. This road connects the cities of Quebec and Saguenay (Canada), with 159 km through a boreal forest, and has been focus of several studies due to the various environmental impacts. In particular, we used the roadkill data of small and medium-sized mammals along these 68.5km of Highway to analyze (a) what are the effects of varying scales (bandwidth) in the Hotspot analysis on the configuration of fencing, (b) to predict the effectiveness of configurations of fence generated by the different scales, and (c) to develop an Adaptive Fence Implementation Plan that maximize the mortality reduction and the connectivity among the regions. We believe that the result of this paper will be extremely useful to researchers and practitioners to identify in a cost-effective manner the most efficient configuration of fence and formulate new approaches to road safety, wildlife management, road design.

2. Literature review

2.1 Direct and indirect effects derived from road construction

The construction of road infrastructure jeopardizes the long-term persistence of wildlife populations or even the survival of a species.

It is possible to group all the consequences that the construction of a linear infrastructure produces and classify them according to different themes (table 1).

Table 1: Effects of landscape fragmentation on the environment and various ecosystem services

Theme	Consequences of linear infrastructure facilities
Land cover	• Land occupation for road surface and shoulders • Soil compaction, sealing of soil surface • Alterations to geomorphology (e.g. cuts, embankments, dams, stabilisation of slopes) • Removal of vegetation, alteration of vegetation
Local climate	• Modification of temperature conditions (e.g. heating up of roads, increased variability in temperature) • Accumulation of cold air at embankments of roads (cold-air build-ups) • Modification of humidity conditions (e.g. lower moisture content in the air due to higher solar radiation, stagnant moisture on road shoulders due to soil compaction) • Modification of light conditions • Modification of wind conditions (e.g. due to aisles in forests) • Climatic thresholds
Emissions	• Vehicle exhaust, pollutants, fertilising substances leading to eutrophication • Dust, particles (abrasion from tyres and brake linings) • Oil, fuel, etc. (e.g. in case of traffic accidents) • Road salt • Noise • Visual stimuli, lighting
Water	• Drainage, faster removal of water • Modification of surface water courses • Lifting or lowering of groundwater table • Water pollution
Flora and fauna	• Death of animals caused by road mortality (partially due to attraction of animals by roads or railways: 'trap effect') • Higher levels of disturbance and stress, loss of refuges • Reduction or loss of habitat; sometimes creation of new habitat • Modifications of food availability and diet composition (e.g. reduced food availability for bats due to cold air build-ups along road embankments at night) • Barrier effect, filter effect to animal movement (reduced connectivity) • Disruption of seasonal migration pathways, impediment of dispersal, restriction of recolonisation • Subdivision and isolation of habitats and resources, breaking up of populations • Disruption of metapopulation dynamics, genetic isolation, inbreeding effects and increased genetic drift, interruption of the processes of evolutionary development • Reduction of habitat below required minimal areas, loss of species, reduction of biodiversity • Increased intrusion and distribution of invasive species, pathways facilitating infection with diseases • Reduced effectiveness of natural predators of pests in agriculture and forestry (i.e. biological control of pest more difficult)
Landscape scenery	• Visual stimuli, noise • Increasing penetration of the landscape by roads, posts and wires • Visual breaks, contrasts between nature and technology; occasionally vivification of landscapes (e.g. by avenues with trees) • Change of landscape character and identity
Land use	• Consequences of increased accessibility for humans due to roads, increase in traffic volumes, increased pressure for urban development and mobility • Farm consolidation (mostly in relation with construction of new transport infrastructure) • Reduced quality of agricultural products harvested along roads • Reduced quality of recreational areas due to shrinkage, dissection, and noise

Note: Examples of the consequences of linear infrastructure facilities such as roads, railways and power lines (not including the effects of construction sites such as excavation and deposition of soils, vibrations, acoustic and visual disturbances). The effects are grouped into seven themes.

Source: Jaeger, 2003, based on various sources.

These multiple alterations, whose individual impacts may be relatively minor, in combination with others may have a synergetic effect, and compromise the sensitive environmental balances to such an extent that even a small negative change will be sufficient to lead drastic consequences in the entire ecosystem quality and functionality. Cumulative effects can be difficult to predict and manage due to inadequate environmental baseline data, complex ecological processes, and the large scale at which human development occurs.

Besides all these direct effects, the construction of a road enables human access to wildlife habitats, unleashing a Pandora's box of environmental ills, such as deforestation, wildlife and timber trafficking, mining and exotic species invasions. In Brazilian Amazonia, 95% of all deforestation occurs within 5.5 km of a paved or unpaved road (Laurance et. al. 2002). Similar trends are evident in Cambodia (Clements et. al. 2014), Sumatra (Miyamoto M. 2006), Thailand (Cropper, Puri, and Griffiths, 2001) and Panama (Sloan and Pelletier, 2012). and occur even inside some legally protected areas (Aldwaik and Pontius 2012). In Peninsular Malaysia, a systematic survey revealed that 90% of snares and poaching camps were located within 5 km of a paved road (Clements et. al. 2014).

The real consequences should be considered analyzing simultaneously the different effects. However, to permit the analysis and design mitigation measures to permit the analysis and design mitigation measures it is possible to group the main effects in traffic mortality, population subdivision, inaccessibility and habitat loss.

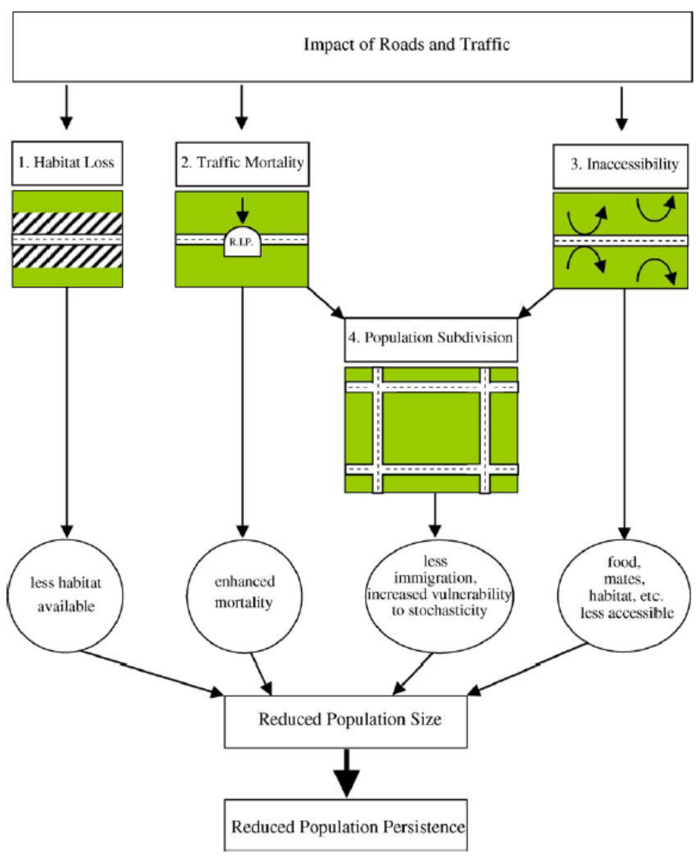

Figure 1: Principal impact of road and traffic on wildlife populations

2.2 Traffic mortality:

To encounter their biological needs, animals often attempt to cross the road, and the amount of animal killed depends principally on the aversion to roads of the species and the amount of traffic on the road. Species that have large area needs, low car avoidance and low reproductive rates are very sensitive to road mortality, and if a significant proportion of the population is killed on roads, and this increased mortality is not compensated by higher birth rates, population persistence can be compromised after one or two generations. (Fuller, 1989, Bangs et al., 1989, Andrews, 1990, Newton et al., 1991) The number of casualties seems to be steadily growing as traffic increases and infrastructure networks expand and is a function of the density and activity of animals and vehicles. Various studies have confirmed road mortalities become a relevant problem at a moderate level of traffic, as shown in Fig. 2. Empirical data on moose-vehicle collisions in Sweden (Andreas Seiler, J-O Helldin, 2006) demonstrated in fact that, when Average daily traffic is between 2500 and 10000 vehicle per day, a great number of the animals that approach the road, not seeing this as a total barrier, will attempt to cross, but only a few of them will succeed. At low (<2,500 AADT) and very high traffic volumes (>10,000 AADT) the number of causalities is relatively low; in the first case because the majority of the animals manage to cross the road and in the second because the majority of the animals will more likely be repelled by traffic noise or vehicle movement.

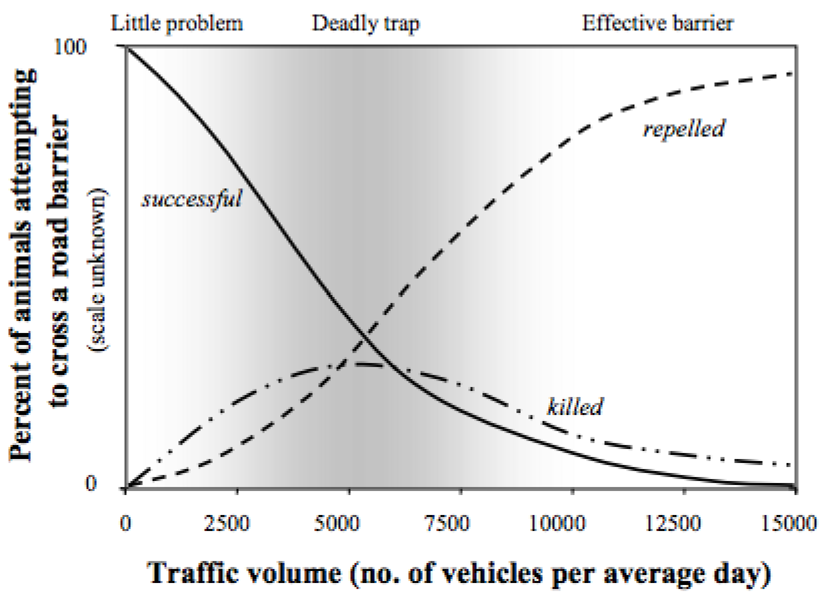

Figure 2: Conceptual model on the effect of traffic volume on the percentage of animals that successfully cross a road, are repelled by traffic noise and vehicle movement, or get killed as they attempt to cross. The model is partly based on empirical data on moose-vehicle collisions in Sweden

Traffic mortality is the most directly observable effect that the infrastructure produces and, according to different studies, the one that presents the strongest negative effect on the probability of persistence. (Jaeger and Fahrig 2004; Jackson and Fahrig 2011; Ascensao et al. 2013). However, while the carcasses along the road represent undeniable evidence of the negative effects of the road, a low rates of mortality on a busy highway shouldn't be interpreted as evidence that impacts are negligible to wildlife since, without mitigation measure aimed at increasing the connectivity among the regions, population reduction will be a consequence of population subdivision and inaccessibility.

2.3 Population subdivision

The construction of a road isolates local subpopulations from the rest of the metapopulation, increasing the risks of inbreeding within populations, and imposes barriers that impede the recolonization of some areas. The result is a reduction in the genetic variability that, in the long term, make weaker wildlife populations, and increase their risk of becoming extinct (Forman and Alexander, 1998; IUCN, 2001). Population abundance on a very fragmentized landscape shouldn't be interpreted as evidence that impacts are negligible to wildlife since, due to the inhibited connectivity between the different habitats, the effect will appear with a time lag, and the consequences of the population subdivision may be seen unanticipatedly after several generations. Preserving a network among the different local subpopulations is therefore fundamental for avoiding the subdivision of animal populations into smaller and more vulnerable fractions, and guarantee genetic variability.

2.4 Inaccessibility

Many animals regularly move to different habitats to meet their daily, seasonal and basic biological needs, and the construction of a road limit their movement, sensibly reducing their chance of survival. Inaccessibility has becoming a urgent problem for many species since the uncontrolled construction of road drastically fragmentize the habitat, forcing them to find the resources vital for their survival in restricted and unbearable areas. The new infrastructures in fact often present several lanes and great amount of traffic, and act as a total barrier for the movement. Preserving a network among the different areas is therefore fundamental, in particular for the areas that present species with large area needs and high avoidance behavior, and result very sensitive to inaccessibility.

2.5 Habitat loss

The construction of a road alters huge areas of untouched environment and destroy the living places of hundreds of species. The reduction of habitat is not only limited by the physical area occupied by the infrastructure, but is extended for several kilometers due to the long-ranging traffic emissions that the road produce. Noise, light and pollutants make unbearable the area close to the road, and bring to the decline of the populations that are not able to respond promptly to the alteration of their habitat. Forman (2000) has estimated that 20% of the land surface in the United States is impacted by roads alone.

Species that have large area needs and low reproductive rates tend to be the most sensitive to the habitat loss, and present great reduction in the population size immediately after the construction of the road.

Furthermore, since the construction of a road enables human access to wildlife habitats and enhance illegal activity such as deforestation, timber trafficking and mining, the destruction of habitat is often much greater than the one produced by the road itself, irreversibly endangering entire ecosystems.

2.6 Wildlife-vehicle collision and road safety

Collisions between wildlife and vehicles can be extremely hazardous and have deadly consequences for both people and animals.

The presence of animal along the road represents a significant risk-factor to road safety since their behavior is unpredictable and drivers cannot anticipate which direction the animal will move.

Though human fatalities resulting from WVCs are relatively rare, roughly 4–10 percent of reported WVCs involving large animals result in injuries to drivers and their passengers. While this may not appear to be a large percentage, only on the American highways this translates into approximately 26,000 injuries per year that are attributable to these accidents (Federal Highway administration, report 2008).
These numbers are even higher in wilderness regions, where wildlife populations are still abundant. WVC in Alberta, for example, account for 50% of all collisions in the highway network, resulting in numerous injuries and fatalities every year and costing Albertans 300'000 dollars a day. (Alberta Traffic Collision Statistics 2016)
As well as human injuries and fatalities, to which is difficult place value, the direct and indirect costs associated with wildlife-vehicle collisions can results extremely high, in particular when the animals involved are large ungulates or great sized animals. Based on numerous studies, the average cost of repairing a vehicle after colliding with a deer was estimated at \$1,840. For collisions with elk and moose, the averages increase to \$3,000 and \$4,000, respectively. (Federal Highway administration, report 2008). If an injury occurs, drivers and passengers may face expenses from emergency services, medical care and possibly lost wages from missed work. Furthermore, transportation agencies typically are responsible for carcass removal and disposal costs and infrastructure repair costs and may incur in some financial losses based on the monetary value of the animal itself. Other indirect costs can derive from emotional trauma, queues and travel delays. The total costs associated with animals-vehicle collisions could be so high that, in some areas, may be even greater than the costs associated with implementing mitigation measures aimed at keeping these animals from accessing the highway and at providing safe crossing opportunities (Huijser et al. 2009). Nonetheless, very few cost-benefit analyses exist and although this may seem surprising, wildlife-vehicle collisions, at least until recently, are not always included in safety analyses by transportation agencies, and in many roads, mitigation measures are evaluated only in relation to their costs of implementation. Poor mitigation plans will result in the implementation of cheap and inefficient mitigation measures, that may not only underestimate the safety risk but may also create the unjust impression that the problem has been solved and further measures are not needed.

Some regions realized the urgency of the problem and started to implement wise monitoring plans to determine the magnitude of the issues and include in the design of the road information that can be used to avoid unexpected scenarios and increase the efficiency of the investments.

2.7 Proactive plans and mitigation techniques to reduce wildlife-vehicle collisions and provide sustainable design

The most effective way to promote road safety and provide long term protection to landscapes, ecosystems, and species is by proactively zoning Earth's land regions and sub-regions. Through wise planning, roads can be built close to existing settlements and create positive outcomes for economic growth and social integration while avoiding numerous environmental, economic and socio-political problems. A critical reason for pushing proactive planning is that EIA assessments for large-scale road projects are usually seldom sufficient for appropriate risk assessment since the interactions among infrastructures and nature are large and potentially unexpected. (Jaeger, 2015).

By the physical division of areas, development could be concentrated in suitable zones, increasing transport efficiency and road safety, and sensitive environments would have the chance to nurture the deep relationships that guarantee their survival.

When these zoning is not achievable, road safety and wildlife population persistence can be enhanced through the implementation of plans and mitigation measures that reduce the interactions among maneuvers and wildlife.

Over 40 such mitigation measures have been implemented and tested in studies, and can typically be divided into two categories: those that influence motorist behavior, and those that influence animal behavior (Hedlund et al. 2004). Motorist behavior can either be altered in such ways that awareness of the possible presence of animals is increased, or motorist speed is reduced to an extent that if an animal were to appear on the road, there would be enough time to react safely. Motorist awareness measures is increased through general education programs, where either through ads or campaigns motorists are made aware of the dangers posed by wildlife-vehicle collisions (WVCs) and thanks to on-the-road awareness measures such as “caution: deer” signs and lighted warning signs.

These adjustments could be determinant, in particular from a safety point of view, since decreasing perception times and speed would produce, as well as a diminution of collisions, a reduction in the impact’s energy. Thanks to proactive plans aimed at increasing the consciousness of the maneuver it is possible to drastically increase the chance of getting away unscathed, in particular in areas populated by large size ungulates where the collisions could produce serious injuries. Another way to reduce speed is through reducing posted speed limits on roads; however, these mitigation measure has been shown to reduce WVCs only if the road is actively patrolled by law enforcement (Lavsund and Sandegren 1991; Hedlund et al. 2004).

Animal behavior near roads can be altered to either reduce animal presence around the road surface, or encourage animals to cross roads at designated locations. The most implemented techniques used alter wildlife behavior are wildlife reflectors, olfactory repellents, ultrasonic warning whistles, habitat alteration, changes in road-verge management, wildlife fences, wildlife crosswalks, and wildlife crossing structures (Iuell et al. 2003; Clevenger and Ford 2010; Huijser and McGowen 2010).

Many researchers agree that the most effective and robust way to reduce collisions is combining wildlife fencing and wildlife crossing structures (Huijser et al. 2009). Highway fencing is at its most effective if it seeks not to prevent animals crossing the road, but rather to direct them to safer crossing points. The combined use of these two measures improve human safety, reduce property damage and decrease the risk of local population extinction due to wildlife mortality and/or population isolation.

Various handbooks offer suitable specifications about how and where the fence should be built, and suggest how to consider in the design relationships between roadkill patterns, landscape and species, and how to combine the various mitigation measures to improve the effectiveness in reducing wildlife-vehicle collisions.

2.8 Fence design, and information provided by the literature about how to consider the fence end effect

The main function of wildlife fencing is to keep wildlife off the highway and decrease wildlife-vehicle collisions. However, a wise design should combine different mitigation measures to simultaneously achieve different goals. Besides this main function, wildlife fencing should help funnel wildlife to safe crossing opportunities, allow wildlife that ends up in the fenced road corridor to escape, warn drivers for wildlife that may cross at fence ends and allow humans to get in and out of the fenced road corridor.

Fence Material and Dimensions

To keep off wildlife from the road, fence material and dimensions should be tailored to the species in the analysis.

For ungulates like deer (*Odocoileus spp.*), elk (*Cervus canadensis)*, and moose (*Alces alces*), fence height for woven wire mesh fences is typically set at about 2.4 m (8 ft). This height may need to be taller (3.0m) in case the target species are capable climbers, e.g. black bear (*Ursus americanus*), and Florida panther (*Puma concolor coryi),* and should be buried (approximately around 1.1 m) in case the target species can dig.

Mesh wire is available in different gauges. Generally, the fence presents a uniform mesh, with a size of approximately 15-18 cm (6-7 inches) (Kruidering et al., 2005; Clevenger & Huijser, 2011). The posts of a woven wire mesh fence for ungulates are usually made in treated wood, and spaced every 4.2-5.4 m.

For medium-sized mammals alone the height of the fence is much lower. A height of about 1 m (3.3 ft) appears sufficient for most medium-sized mammal species, except feral cats and red foxes, who may require higher fences (1.8 m = 6 ft), unless the fences are electrified (Robley et al., 2007). One of the most used mesh size is 10.2 x 5.1 cm (4 x 2 inches) with electrical wires along the bottom (about 9 cm = 3.5 inches above the ground) and at the top to prevent animals from digging under or climbing over (Smith et al., 2013).

If multiple types of fencing are required for different target species they can often be combined into one design (Kruidering et al., 2005). In case of the simultaneous presence of large and medium-sized species, the fence should present smaller meshes (8 cm (3 inches)) at the bottom of the fence to exclude both from the road (Kruidering et al., 2005; Clevenger & Huijser, 2011).

Fence Location and Length

Wildlife fencing should typically be implemented on both sides of a road in locations where concentrations (“hotspots”) of wildlife-vehicle collisions occur, to keep off a greater number of animals. However, since animals that approach the fence may decide to walk until his end and sidestep it, to be effective in reducing wildlife-vehicle collisions, the fence needs to extend further than the actual hotspot (e.g. Bissonette & Rosa, 2011). By definition, road sections with relatively long and contiguous wildlife fencing (e.g. at least several miles or kilometers) are less likely to have a fence-end run issue than relatively short road sections with wildlife fencing (e.g. up to several hundred yards or meters). For long road sections, in fact, the road length around the fence ends where a fence-end run may occur is relatively short compared to the total road length than is fenced, and the probability that the animals within the fence are kept off by the fence is usually high. However, long sections of fence could generate an impenetrable barrier for animals, and mitigation measures that consent connectivity (wildlife crossing structures) and that allow animals to escape from the fenced road corridor (One-Way Gates, escape ramps) should be always implemented in the design.

To maximize the efficiency of the fence, and implement stretches of fence that are not so long to waste resources where there are few animal fatalities, and not so small to be easily sidestepped, the design of the fence should be tailored on the home range of the animals in the analysis and should consider how likely are these to persevere long enough to sidestep the fence.

Fence end

Considering where and how the fence end, could highly increase the efficiency of the fence at reducing wildlife-vehicle collision. To reduce the fence-end effect and increase connectivity among regions, the topography of the area should be also considered in the analysis, and the fence end should be designed in suitable areas, where wildlife can easily cross, or where can be easily detected by maneuvers. Steep slopes (road cut or fill), river crossings, or areas with relatively high levels of human presence and disturbance are good examples of where the planner may choose to have a fence end. Measures aimed at alerting the maneuver of the possible presence of the wildlife, such as animal detection system and wildlife sign, and measures aimed at keeping wildlife from wandering off in the fenced road corridor, such as wildlife guards and electric mats, should be always considered.

Fence ends should finish opposite of each other, to reduce the probability that these wander off into the fenced road corridor rather than cross at grade at a fence end. To further reduce the probability of fence end effect, wildlife fence is usually angled away from the road at a fence end. In some cases, the fence angles only slightly away from the road (e.g. 45°) whereas it is 90° (perpendicular) to the road in other cases (Kruidering et al., 2005). There are also examples where the wildlife fence first angles away from the road at 90° and then bends back another 90° essentially paralleling the main fence for some distance (Kruidering et al., 2005). In some cases, however, the fence angles towards the road surface at a fence end. An angled fence discourages animals from wandering off into the fenced right-of-way but does not help avoid a fence-end effect, so his implementation should be carefully considered.

To achieve simultaneously both these objectives, boulder fields may be implemented at the fence end to discourage wildlife, specifically ungulates, from crossing the road or walking into the fenced road corridor.

Wildlife crossing structures

At grade crossing opportunities for large mammals – with or without accompanying animal detection systems - are typically only implemented along relatively low volume highways (a few thousand up to perhaps 14,000 vehicles per day at a maximum).

For high volume roads (certainly for highways with more than 15,000 vehicles per day), a physical separation of traffic and wildlife is almost always advisable (Construction guideline for wildlife fencing, Huijser & al). In that case, wildlife fencing and wildlife crossing structures should be designed together, considering objective, target species, structure effectiveness, engineering constraints due to terrain, costs for construction, maintenance, improvements to highway safety, and aesthetics. Fences are fundamental since, without them, most of these animals would not use the structures (Clevenger et al 2001). The combined design of these two measures not only keeps animals off from the road, reducing the number of wildlife-vehicle collisions, but funnel these to safe crossing passages, increasing the connectivity among the regions severed by the road (Huijser et al. 2009).

The most implemented wildlife crossing types consist of over-grade crossing structures (wildlife overpasses), and below-grade crossing structures (wildlife underpasses).

Wildlife overpasses are often the most effective wildlife crossing and benefit the largest number of species. Usually made in concrete and subsequently covered with soil and vegetation, to meet the need of the market and reduce the relatively high cost, recent studies designed lower-cost solutions, creating crossing structures that still present high efficiency made of wood or metal construction (e.g. Voelk et al., 2001; ADAC, 2008).

Wildlife underpasses instead can be specifically designed (Multi-plate arches, open span bridges, and bridge extension), or can be derived in a cost effective manner adapting viaducts and culverts for wildlife use. Emerging research has found in fact that in addition to wildlife over- and underpasses, structures not originally designed to facilitate animal movement may be playing a vital role in allowing animals to cross under roads in areas without any designated wildlife crossing structures (Clevenger & Barrueto 2014). Drainage culverts, designed to allow water to pass freely under roads, also assist many species in crossing roads (McDonald & St Clair 2004), and one study found that the implementation of culverts and exclusion fencing brought a reduction of 93.5% in traffic-related animal mortality (Glista et al. 2009). Further research into the effectiveness of drainage culverts as wildlife passages is paramount in part due to the minimal cost of maintaining or adapting already existing structures to serve both hydrological and ecological needs (Mata et al. 2008).

2.9 Evaluation of wildlife-vehicle collisions

The collection and interpretation of WVC data is critical in helping researchers and practitioners formulate new approaches to road safety, wildlife management, road design.

Wildlife-vehicle collisions are not random occurrences but are spatially clustered, and the identification of the areas with the densest aggregations allow to design a cost-effective configuration of fence, prioritizing the sections in which the fence is more needed.

Many studies predict the areas with the highest rate of WVC grouping relevant landscape and road-related factors into multivariate models. Variables used by these models include anthropogenic land use, wildlife habitat and terrain, integral spatial relationships such as type, shape, size or configuration of a species preferred habitat with respect to roads, and road factors such as traffic volume, road alignment, motorist visibility and road grades (e.g. Seiler 2005).

However, statistically significant models that include numerous variables render confusing results, since some of these variables can interact and bring to confusing interpretations. For example, it is difficult for a transportation planner to know whether clearing roadside vegetation will decrease WVC because motorist visibility is increased or be counterproductive because ungulates are now attracted to roadsides for foraging (Gunson et al. 2011).

The most effective way to predict where the WVC will occur is achieved by modeling the spatial pattern of the wildlife-vehicle collision along the road. Once WVC are collected through a road mortality survey, it is possible to perform spatial and temporal analyses and identify the sections along the road in which the implementation of the mitigation measure is more effective.

The most used techniques used to identify non-random cluster of WVCs along roads are Linear nearest neighbor analysis, Kernel density estimation, Density measures WVCs per mile segment, and Hotspot Identification analysis.

Linear nearest neighbor analysis
Linear nearest neighbor analysis is a quick and easy statistical test of spatial distribution to initially determine whether collisions are distributed randomly across a stretch of highway. A first-order linear neighbor index (NNI) is used to evaluate if the distribution of the observed WVC in a region differs from a random distribution. The NNI is a ratio between the mean nearest distance to each WVC [d(nn)]and the mean nearest distance that would be expected by chance [d(ran)] NNI = d(nn)/d(ran). If the test indicates NNI < 1, then the subsequent step would be identifying where the clusters occur, using spatial analysis techniques.

Density measures WVCs per mile segment
Density measures WVCs per mile segment can be calculated recording the UTM coordinates for each mile marker location and moving each carcass location point to the nearest mile marker reference point. This analysis is usually used to identify relation among amount of roadkill, landscape, human use, species, and to evaluate the distribution of the observed WVC but it is not efficient to design mitigation measures, since it moves the carcass data far away from the location in which are detected, and make impossible the design of an accurate configuration of fence.

Kernel density estimation
Kernel density estimation is a statistical testing procedure that uses second-order distance statistics to determine which clusters within a road section are statistically significant. To do this, it considers the complete distribution of all distances in the point pattern and determines, for each cluster, a degree of significance, weighting the distances of all the data points. The advantage of using the Kernel density estimation is that it is possible to compare the different clusters, and prioritize the areas with the highest risk.

Hotspot Identification analysis
Hotspot Identification analysis exploits the nearest neighbor hierarchical technique to identify a series of points that are spatially close and group them based on a predefined set of criteria. The minimum number of point required to define a cluster and the badwith (scale) are set a priori, and the clustering is repeated until either all point (WVCs) are grouped in a single cluster, or else the clustering criterion fails. The advantage of using this analysis is that this technique reduces the blurring of WVC hotspot on long stretches of highway and allows identifying locations of the sections that present a higher concentration of points than expected from a random distribution. To identify clusters along the road, the density of points within a defined area is compared against a complete spatial randomness model, which describes a process in which point events occur completely at random (i.e., homogeneous spatial Poisson process). Hotspot intensity values greater than the upper confidence limit indicate hotspots, while hotspot intensity values lower than the lower confidence limit indicate coldspots, and all other values between the hotspots and coldspots indicate warmspots. The results of the analysis are Hotspot intensity values enable a better comprehension of the spatial configuration of roadkill.

Modelling the spatial pattern of the wildlife-vehicle collision with these techniques allow the implementation of more efficient mitigation measures. However, even with this information, the design of these is often a challenge for road planners and ecologists.

The identification of the regions, and consequently the configuration of fence, change by varying the bandwidth with whom the spatial configuration of roadkill is analyzed, and due to the presence of the fence end effect, relationships between roadkill pattern and species are necessary.

Stretches of fence not sufficiently long would result inefficient, since instead of preventing the roadkill would move them adjacent to fence-ends, while stretches of fence too long would be uneconomical, since would unduly incorporate low-density areas. In order to implement the ideal mitigation, the bandwidth in the analysis should be coherent with the home ranges of the animals in the analysis. While a scale too fine would create the first circumstance (many short sections of fence inefficient due to a high probability of fence-end effect), a too coarse-scale would result in the second (few long sections, extended to parts of the road in which it would not be needed).

Moreover, fences should be designed not only to reduce roadkill but also to maximize the connectivity among regions, and relationships between roadkill patterns and landscape should also be considered in the analysis. To further reduce wildlife-vehicle collision and increase connectivity among regions, the fence end should be designed in suitable areas, where wildlife can be easily detected by maneuvers, and measures aimed at alerting the maneuver of the possible presence of the wildlife, such as wildlife sign and animal detection systems, should be considered in the analysis.

Finally, due to financial issues, wildlife crossing structures could be built only in specific points of the road, adapting viaduct or existing structures for wildlife use. In this case fence design is even more challenging, since the areas with the highest rate of collisions may be far from the existing wildlife crossing structures, and the planner may have to choose if it is more convenient to extend the fence and provide a safe cross to the animal within the fence (while inevitably fencing areas with low rate of collisions) or leave an at-grade crossing and use the same length of fence to protect other road sections that present an higher roadkill density.

Due to geographic constraints, species of concern and highway characteristic, the analysis of the study area is fundamental for an efficient design, and each case require a site-specific planning.

2.10 Historic introduction of the park (PNJC, RFL) and presentation of the mitigation measures of the study area

This study took place in the province of Quebec (Canada) along Hwy 175 (Fig.3). This road connects the cities of Quebec and Saguenay, with 159 km through a boreal forest dominated by balsam fir (*Abies balsamea*) and black spruce (*Picea mariana*). The road crosses the *Réserve faunique des Laurentides* and borders the *Montmorency Forest* and the *Parc National de la Jacques-Cartier*. Elevation in the study area varies between 163 and 859 m. On average, annual snowfall amounts to 593 cm between October and May, and the area receives 948 mm of rain per year (Bouffard et al., 2012). The annual average daily traffic (AADT) on HW 175 was 5900 vehicles per day during the years 2011–2015 (annual increase 2% per year; proportion of trucks 15%). In the summer months (June–September), this average was almost 30% higher (7560 veh./day), and about 20% lower (4680 veh./day) in the winter months (December–March) (personal communication Gabriel Langevin, Ministere des Transports, de la Mobilite durable et de l’Electrification des transports du Quebec).

Between 2006 and 2012, Hwy 175 was widened from two to four lanes, increasing his average daily traffic and tripling the width of the right-of-way from 30 m to 90 m. To improve driver’s safety, and to help mitigate the effects of the expansion, 67 km of fences for large mammals and 33 wildlife crossing structures for medium and small sized mammals were planned between kilometers 60 and 144. By 2012, only 19 of the planned 33 small fauna passages made for mammals smaller than wolves (< 30 kg) were installed, adapting culverts and viaducts for wildlife use, as it is shown in Fig.4. Unitedly at these, fences designed for medium-sized animals were built on both sides of every passage to direct these towards passage entrances. Each fence was about 100 m long on either side of the entrance and 90 cm high with a 6 cm mesh size. The focus of this study is on road mortality of animals as small as the shrew (Soricidae spp.) and as large as the gray wolf (Canis lupus).

Surveys consisted of a vehicle driving at 70 km/hr in the right lane with one driver and one principle observer in the passenger seat. When a road-killed animal was detected a Global Positioning System (GPS) point was taken to record the geographical coordinates of the mortality. In total, 839 roadkill locations were recorded, belonging to 13 different species (*Plante et al. 2018, 2019 and Spanowicz et al. 2017)*, which average home range in summer sizes from less than 1 ha (for micromammals) up to 4400 ha (for Canadian lynx).

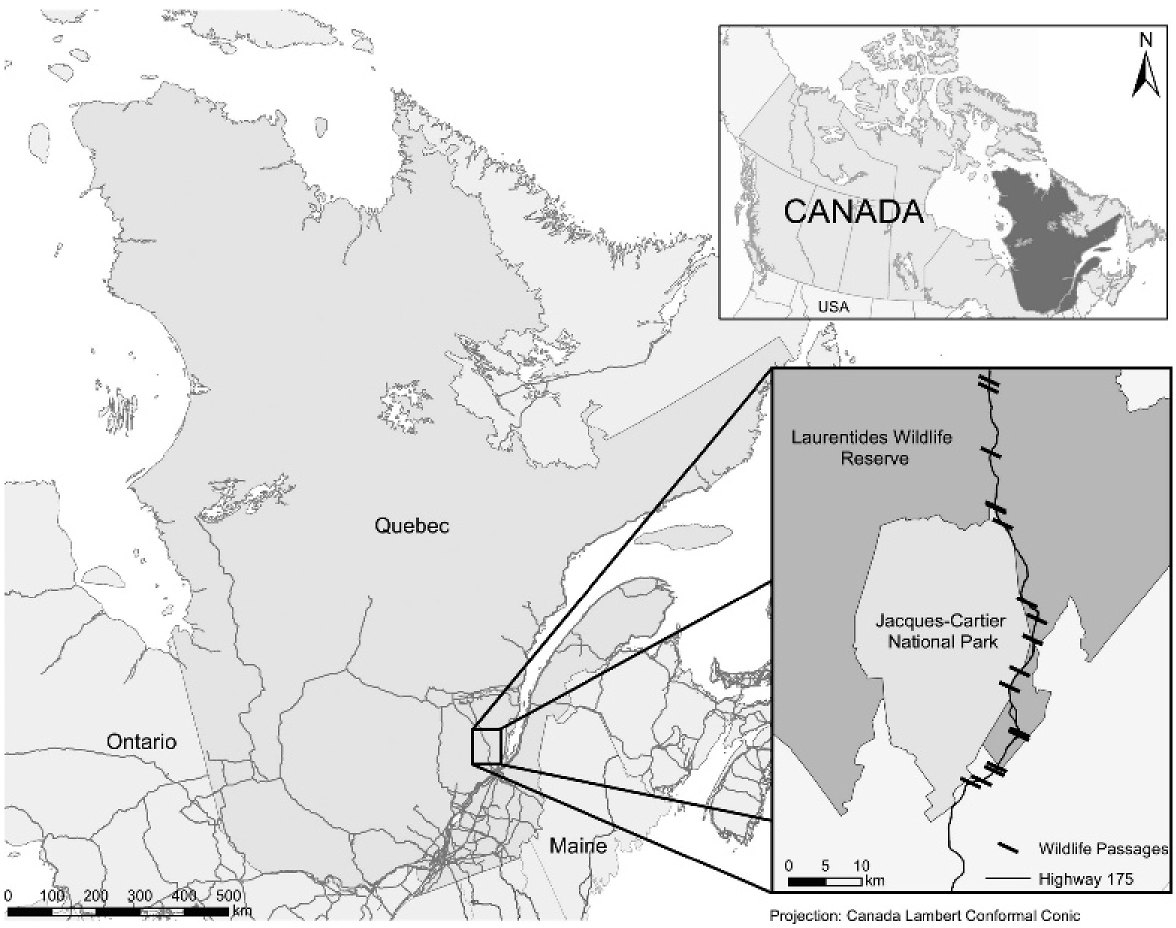

Figure 3: Map of the study area

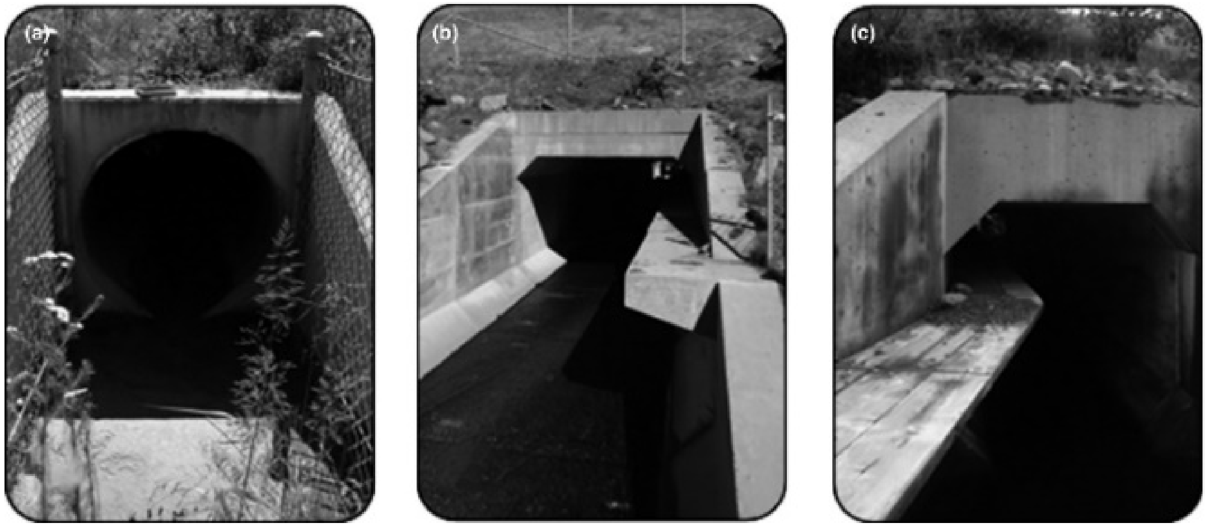

Figure 4: Culverts adapted for wildlife use

2.11 Research questions

To help managers to identify where fences should start and end, and how long these sections should be prolonged to prevent the fence end effect, we analyzed with multiple scales and confidence levels the roadkill data of small and medium-sized mammals along Highway 175 through a Hotpot Identification Analysis, answering the following research questions:

1) What are the effects of varying scales in the analysis on the configuration of fencing and which scale would have the highest benefit without considering the fence-end effect?
2) Which scale would result in the highest benefit, while considering the fence-end effect?
3) How can the information provided by the different scales be combined in a meaningful way to improve even more the efficiency of the fencing?

The answer of the first two research questions enabled a better comprehension of the problem, and brought us to develop process of optimization that, through the simultaneous use of various scales and considerations on the probability of success that each stretches of fence present, identify in a cost-effective manner the most advantageous configuration of fence.

Prioritizing road sections for wildlife fencing

Abstract

Road mortality has various detrimental effects on the abundance, persistence probability, and genetic diversity of wildlife populations.

Available evidence indicates that one of the most effective mitigation measure to date is the combined use of sections of fence in high-risk areas and wildlife crossing structures. Their combination not only allows to decrease road mortality, preventing the animals from accessing the road, but funnel these to safe crossing passages, increasing connectivity among the regions that have been disjointed by the road.

Fencing certain road sections may be more efficient than fencing other sections, which can be identified through a hotspot analysis of the spatial configuration of roadkill patterns. However, varying the scale at which the spatial pattern is analyzed may affect the locations identified for mitigation measures and their predicted effectiveness. Even with the knowledge of the spatial pattern of the wildlife-vehicle collision the identification where fences should start and end, how long the sections should be prolonged is often a challenge for road planners and ecologists.

While a very fine scale results in many sections of fence that may be inefficient due to a high probability of a fence-end effect to occur, a very coarse-scale would result in the implementation of fences parts of which would not be needed. Spanowicz et al. called this trade-off between the total number of fence sections and the length of the fences the FLOMS ("Few-Long-Or-Many-Short [fences]") trade-off.

To help managers to predict the effectiveness of configurations of fence we created a model that estimates the probability of success of the implemented sections as a function of the length of the section and the home range size of the species, and we combined the results of this model with the ones of the Hotspot Identification Analysis along Highway 175. We then used the results obtained to discuss the fence-end effect and the FLOMS trade-off, demonstrating that an overestimation of the scale used in the analysis is often preferable.

To further increase the effectiveness of the mitigation measure we developed an Adaptive Fence Implementation Plan that, through the combination of different scales of hotspot analysis, and through considerations on species and wildlife crossing structures, identifies the configuration of fence that maximize the mortality reduction and the connectivity among the regions.

We believe that the result of this paper will be extremely useful to researchers and practitioners to formulate new approaches to road safety, wildlife management, road design.

3.1. Introduction

3.1.1 Road mortality

The construction of road infrastructure severs many ecological relationships in complex ecosystems, and results in various effects that in many cases drastically compromise the abundance and persistence probability of wildlife populations living the area (Fahrig and Rytwinski 2009; Bennett 2017; Forman and Alexander 1998). In particular, roads enhance wildlife mortality due to collisions with vehicles, reduce and fragment wildlife habitats, and act as barriers to movement for the animals. Besides being the most directly observable effect of roads and traffic, available evidence indicate that the wildlife mortality associated with road crossing attempts may in many cases have a stronger negative effect on the size and the probability of persistence of populations than the reduction in movement between habitat patches (Jaeger and Fahrig 2004; Jackson and Fahrig 2011; Ascensão et al. 2013). While the effect of loss of connectivity on local populations may often take several generations to manifest, the effects of road-related mortality may be seen in one or two generations (P. Huijser, P. Clevenger 2011)

The most effective way to promote road safety and provide long term protection to landscapes, ecosystems, and species is guaranteeing a physical division, by proactively zoning Earth's land regions and sub-regions or by implementing the road above or Below-grade. When this is not possible, wildlife population persistence can be preserved through the implementation of plans and mitigation measures that reduce the interactions among maneuvers and wildlife. Among these mitigation techniques that keep traffic and wildlife at least partially separated, fencing and wildlife crossing structures, according to different researches (Forman et al. 2003, Jaeger et al. 2016), are believed to be the most effective. Their combination not only allows to decrease road mortality, preventing the animals from accessing the road, but funnel them to safe crossing structures, increasing connectivity among the regions that have been disjointed by the implementation of the road (Elizabeth Rose Fairbank 2014; Mattias P. O. Olsson 2008).

Wildlife-vehicle collisions (WVCs) are a growing problem not only for wildlife conservation and management, but also for civil engineer, because they represent a significant risk-factor to road safety (Federal Highway administration, report 2008).

The presence of animals on the road often causes a quick change in direction that could lead to the driver’s loss of control of the vehicle. Furthermore, WVCs are costly, and on certain road sections, the long-term costs associated are greater than the costs of mitigation measures aimed at keeping these animals off the road (Huijser et al. 2009).

Considering that the number of casualties is steadily growing as traffic increases and infrastructure networks are expanded, and that humanity is currently living in the most dramatic era of infrastructure expansion in human history (Laurance, W.F., and Balmford, A. (2013)), mitigation measures will be of fundamental importance for long term population persistence.

3.1.2 FLOMS (“Few-Long-Or-Many-Short [fences]”) trade-off

Due to financial constraints, it is rarely possible to fence the entire road. Fencing particular road sections may be more efficient than fencing other sections.

The collection and interpretation of WVC data is critical in helping researchers and practitioners to prioritize road sections; by modeling the spatial pattern of the wildlife-vehicle collision along the road it is in fact possible to identify the sections along the road with significantly higher roadkill numbers than expected from a random distribution, and therefore identify the areas in which the implementation of the mitigation measure is more effective.

However, since animals may choose to move along the fence until its end and cross at grade there, even knowing the spatial pattern of roadkill, the design of mitigation measures is a challenge; the fence should not be limited to the sections with the highest density of animal crossings (hotspots), but should be extended according to the home range of the animals considered in the analysis to prevent the so called “Fence end effect”. The identification of these hotspots, and consequently the sections of fence implemented, changes by varying the scale (or bandwidth) with whom the spatial pattern of roadkill is analyzed; while a very fine scale results in many sections of fence that may be inefficient due to a high probability of a fence-end effect to occur, a very coarse-scale would result in the implementation of fences parts of which would not be needed. Spanowicz et al. called this trade-off between the total number of fence sections and the length of the fences the FLOMS (“Few-Long-Or-Many-Short [fences]”) trade-off.

Various handbooks offer specifications for the type of such fencing suitable for different species and provide suggestions about how they should be built (Wildlife Crossing Structure

Handbook 2011, Handbook of road ecology 2015). However, there are currently no generally agreed guidelines that relate the scale of the hotspot analysis to the species, and there are no information concerning by how much the sections identified should be prolonged to prevent fence-end runs.

3.1.3 Research questions

Crossing structures alone do not effectively mitigate road mortality (Rywinski et al. 2016), and the implementation of fences is an essential component of road mitigation. To address the FLOMS trade-off and implements the optimal configuration of fence, with sections not so long that they would waste resources on areas where few animals are crossing, and not so short to be sidestepped, we investigated the spatial pattern of roadkill along Highway 175.

Analyzing the spatial pattern of roadkill at multiple scales of analysis and several confidence levels we answer the following research questions:

1. What is the effect of varying the scale of analysis on the configuration of proposed fencing, and which scale would have the highest benefit without considering the fence-end effect?

2. Which scale would result in the highest benefit when the fence-end effect is considered?

3. How can the information provided by the different scales be combined in a meaningful way to improve the efficiency of the fencing?

To address the first research question, we evaluated the spatial pattern of roadkill at four scales (300 m, 500 m, 1000 m, 2000 m) and we compared the results of the analysis.
To evaluate the differences in the configuration of fence implemented, we compared a same amount of length (20km) created with the different scales, and we represented the number and the length of the sections of fence produced by each scale.
To evaluate the effect that the scale of analysis present on the density of the aggregations of roadkill detected, we compared, for any length of fencing, the total number of roadkill detected by each scale; not considering the presence of the fence end effect, the roadkill detected can

be considered as prevented, and the assumption that all animals that encounter the fence are prevented from entering the road enabled a first rough prediction of the mortality reduction produced by the different configurations of fence.

We, therefore, presented in the abscises the total fence length and in the ordinate the “Predicted primary mortality reduction” produced by the different scales.

Since not all the animals that encounter the fence are actually prevented by its implementation, to address the second research question and calculate a more accurate value of the effectiveness of the fence we used a model to predict the fence-end effect as a function of the home-range size of the species and we integrated the result of this model at the primary mortality reduction previously detected.

The combination of the results of the hotspot analysis with the ones of the model enabled an accurate estimation of the number of animals actually prevented by the various configurations, and therefore an accurate estimation of the mortality reduction that the implementation of the different configurations would produce. In particular, we used the model on the configurations of 20km of fence previously detected and we determined the scale that would result in the highest benefit while considering the fence-end effect. To visualize if these results were consistent with the other lengths of fence, we applied the same procedure each 10 km of fence, and we created a “Predicted revised mortality reduction graph”.

The different scales can be combined in the same analysis to better understand the spatial configuration of roadkill pattern and to arrive at a more efficient configuration of fence. To address the third research question and further increase the effectiveness of the mitigation measure we developed an Adaptive Fence Implementation Plan that combines various scale in the same analysis and consider home range of the species and the location of wildlife crossing structures. As a final result, we propose 4 configurations of fencing (length of 19.8 km, 23 km, 26.1 km, and 27.7 km) that are predicted to produce higher mortality reduction and higher connectivity than the ones obtained from a single-scale analysis.

We finally give recommendations about their implementation, and we pointed out future research based on which it will be possible to increase further the effectiveness of this scale-combination method.

3.2. Methods

Through the analysis of roadkill data of small and medium-sized mammals along Highway 175, we compared the estimated mortality reductions generated by the different scales and the corresponding maps of the spatial configurations of fencing, to understand how can be reached the ideal intervention.

3.2.1 Study area

This study took place in the province of Quebec, Canada, along Hwy 175. This road connects the cities of Quebec and Saguenay, with 159 km crossing through a boreal forest dominated by balsam fir (*Abies balsamea*) and black spruce (*Picea mariana*). The road traverses the Réserve faunique des Laurentides and borders the Montmorency Forest and the Parc National de la Jacques-Cartier. Elevation varies between 163 m and 859 m. On average, annual snowfall amounts to 593 cm between October and May, and the area receives 948 mm of rain per year (Bouffard et al., 2012). The annual average daily traffic (AADT) on HW 175 was 5900 vehicles per day during the years 2011–2015 (annual increase 2% per year; proportion of trucks 15%). In the summer months (June–September), this average was almost 30% higher (7560 veh./day), and about 20% lower (4680 veh./day) in the winter months (December–March) (personal communication Gabriel Langevin, Ministere des Transports, de la Mobilite durable et de l'Electrification des transports du Quebec).

Between 2006 and 2012, Hwy 175 was widened from two to four lanes, which resulted in increased average daily traffic and in tripling the width of the right-of-way from 30 m to 90 m (Bédard, 2012). To improve driver's safety, and to help mitigate the effects of the expansion, 67 km of fences for large mammals and 33 wildlife crossing structures for medium-sized and small mammals were planned between kilometres 60 and 144 (Bédard et al., 2012) . By 2012, only 18 of the planned 33 small and medium-sized fauna passages made for mammals smaller than wolves (< 30 kg) were installed. Fences designed for medium-sized mammals were built on both sides of every passage to direct animals towards the passage entrances. Each fence was about 100 m long on either side of the entrance and 90 cm high with a 6 cm mesh size. The focus of this study is on road mortality of animals as small as the shrew (*Soricidae spp.)* and smaller as the gray wolf (*Canis lupus*).

3.2.2 Individuals recorded and used in the statistical analysis

We used mortality data from surveys along a 68 km stretch of HWY-175 between kilometers 75.5 and 143.5 (Plante et al. 2018). Surveys consisted of a vehicle driving at 70 km/h in the right lane with one driver and one principle observer in the passenger seat from June to September in 2012 to 2015. When a dead animal was detected, a Global Positioning System (GPS) point was taken to record the geographical coordinates. In total, 839 roadkill locations were recorded, belonging to 13 different species, with average home range size in summer ranging from less than 1 ha (for micromammals) up to 4 400 ha (for Canadian lynx) (Tab. 2).

Table 2: Number, species, and average summer's home range of roadkill identified along the Highway 175 (sources: roadkill data from Plante et al. 2018)

Species list for Highway 175 (Quebec, Canada)			
Common Name	**Scientific Name**	**Number of roadkill recorded**	**Average summer's home range [ha]**
North American Porcupine	*Erethizon dorsatum*	366	65
Red fox	*Vulpes vulpes*	47	1611
Mouse spp.	*Peromyscus* spp.	43	minor
Striped Skunk	*Mephitis mephitis*	42	255
Snowshoe hare	Lepus americanus	41	10
Shrew	Sorex spp.	32	Minor
Vole	Arvicolinae spp.	27	minor
American Red squirrel	Tamiasciurus hudsonicus	17	4.5
Raccoon	Procyon lotor	11	244
North American Beaver	Castor canadensis	7	18
Jumping mouse	Zapus hudsonius	2	Minor
Canadian Lynx	Lynx canadensis	2	4400
Northern flying squirrel	Glaucomys sabrinus	2	6
American mink	Mustela spp.	1	600
Deer mouse	Peromyscus maniculatus	1	Minor
American Marten	Martes americana	1	800
Woodchuck	Marmota monax	46	2.5
Micromammal unknown	Arvicolinae, Peromyscus, Sorex spp.	102	Minor
Mammal unknown	---	49	-
Total	**---**	**839**	

Since the woodchuck (*Marmota monax)* is not native of the study area and has started to spread only after the construction of the road, its 46 records were removed from the dataset for the analysis. The remaining 793 roadkill events were uploaded into Siriema.

3.2.3 Explanation of how Siriema works: 2D Ripley's *K*-Statistics and 2D Hotspot Identification

The road-kill spatial pattern was analyzed using Siriema v.2.0, a software that generates graphs of hotspot intensity along the roads (Siriema, User manual 2.0). In order to evaluate non-randomness of the spatial distribution of events at multiple scales, Siriema uses 2D Ripley's *K* Statistics to identify significant roadkill aggregations ("hotspots") along the road. The process is computed in several steps. For each scale selected, a moving window approach allows to identify the road segments with the highest aggregations of roadkill (hotspots):

- The road is divided in segments of the same length. The higher the number of road segments, the more detailed the analysis.
- A circle of a defined radius (r) is centered in the central point of the first road segment, and the roadkill events within the circle area are counted. This number is multiplied by a correction factor that considers the road length inside the circle.
- The circle is centered on the central point of the next segment and the number of events is computed and multiplied by the correction factor. This process is repeated for all road segments to generate a value of roadkill aggregation intensity for each road segment:

$$H_i(r) = 2r / Ci(r) \sum_{i=1}^{n} fij$$

$H(r)$ = aggregation value for point i considering radius r;

n = number of roadkill events;

r = defined radius;

i = point on road;

j = roadkill event;

$C_i(r)$ = road length inside the circle with radius r centered on point i;

f_{ij} = index equal 0 if point j is outside the circle with radius r centered on point i, or equal 1 if j is inside the circle area.

For evaluating the significance of the aggregations Siriema compares the spatial configuration of roadkill observed with randomizations of the same number of events considering a uniform probability distribution using the following function:

$$HS = H_i(r) - Hs(r)$$

Hs(*r*) = *H* value obtained from simulations of a random distribution of the same total number of events along the road. A confidence interval (CI) is computed from the simulated data, and the value of *HS* from the observed data is compared with the values of confidence interval to determine significance. Values of *HS* greater than the upper confidence limit indicate hotspots, while values of *HS* lower than the lower confidence limit indicate coldspots. All other values indicate warmspots (Spanowicz et al., subm.). Comparing the values obtained with the confidence levels reveals if a road segment presents a higher number of roadkill than the one expected from a random distribution and how confident we are about the result.

For example, a value of *HS* higher than the 95 percent confidence level indicates that, if the analysis were repeated many times with randomized events, the number of random events detected within the same circle will be lower than the ones observed in the field more than 95 percent of the time.

3.2.4 Output of Siriema: images, maps, and Excel

After the 2D Hotspot Identification for each scale and for each confidence level, the output of Siriema provides a table that defines for each segment analyzed (ID) the coordinates of the central point (latitude and longitude) and the values of *HS*, *UCL*, *LCL*, and *Hs*(*r*) (Table 3).

Table 3: Output from the hotspot analysis in Siriema for a 300 m scale (150 m radius), using a 80% of confidence level (number of simuilations was 5000).

Latitude	Longitude	HS	UCL	LCL	Hs(r)
47.11381	-71.3387	-2.16732	2.326085	-2.16732	3.66512
47.11435	-71.3377	-2.64114	1.358769	-1.64116	3.641116
47.11488	-71.3366	-2.60855	1.391376	-1.60857	3.608536
…	…	…	…	…	…

The output will be transferred to Excel in order to perform the calculations required for the mortality reduction graphs and to enable further analysis in R and in QGIS.

3.2.5 Scales used in the analysis and analytical consideration of the fence-end effect

The scales (diameters of the circles, in meters) used to identify roadkill hotspots can be chosen according to the results from Ripley's *K* analysis and according to the researcher's or road manager's goals in relation to potential mitigation measures to be adopted. A good comprehension of how the choice of scales influences the results is fundamental, since the use of some scales could be more efficient than the use of others.

At a superficial look, it seems that scales corresponding to a smaller diameter could prevent more roadkill, since, at parity of total length, they include a greater number of events within them. Fine scales detect the most closely aggregated roadkill patterns, and consequently result in a configuration of fencing that presents many short sections with a high density of roadkill, that can be fenced with a shorter total amount of fence.

However, since animals move great distances to cover their daily needs or to disperse the effectiveness of the sections of fence implemented depends not only on the on the results of the hotspot analysis, but also on the length of the sections. Animals are prevented from being killed by traffic only if the section implemented are long enough to impede them from reaching the fence-end and cross the road at grade there. This phenomenon has been called fence-end effect (Rodney van der Ree 2016) and is more likely to happen to animals that have great home ranges or when the sections of fence implemented are short.

Increasing the diameter of the circle used for the analysis reduce the number of roadkill within the fence, but increase the length of the sections implemented, and therefore the probability of fence success, because the animal that encounter the fence will not so easily be able to move around the fence-ends.

To demonstrate how influential the choice of the scales is on the resulting fence configuration, Fig. 5 shows the same total fence length (1000 m) resulting from the use of a fine scale (300 m) and a coarse scale (1000 m), respectively.

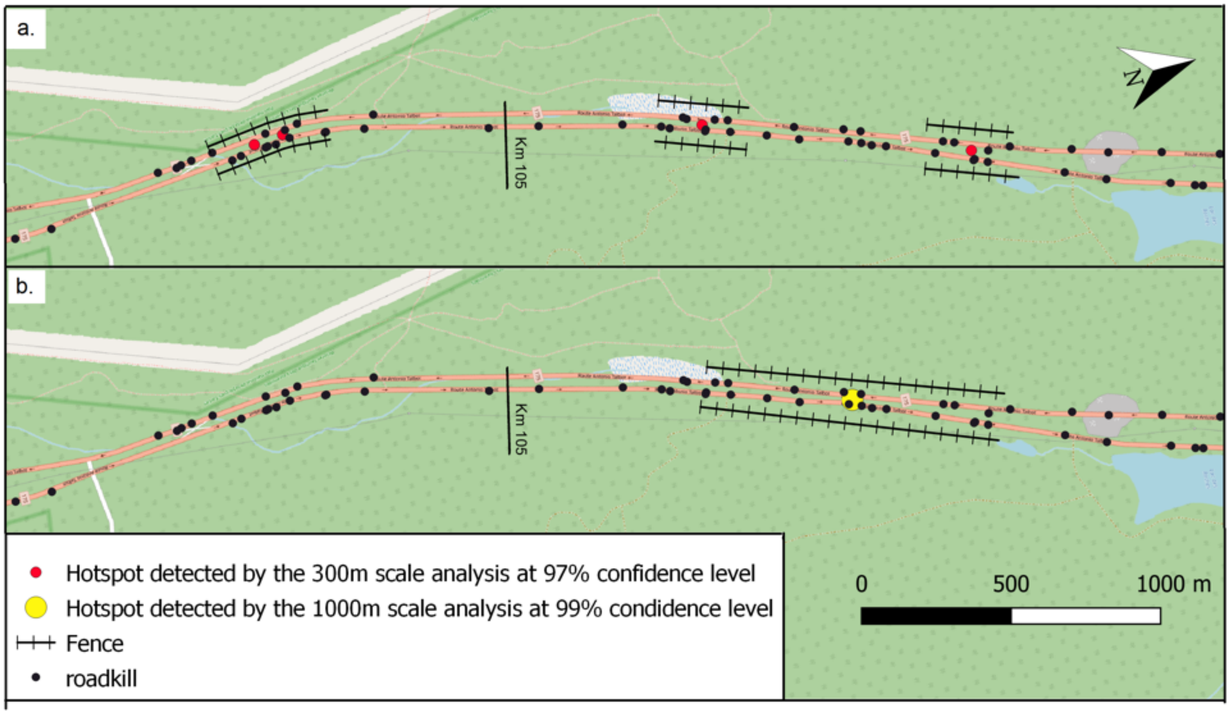

Figure 5: Fencing configurations with same total fence length of 1000 m resulting from a 300 m scale (a) and 1000 m scale analysis (b) using the steps explained in sections 2.4 and 2.6. Number of roadkill events within the fence sections in configuration (a) is 28, while in configuration (b) it is 20.

For the same total fence length, the number of roadkill events enclosed by the finer scale is higher, but the chance that these are actually prevented by the fence in the landscape is lower. In Figure 5, for example, since the diameter of the home range of many animals used in the analysis (Tab. 2) is much larger than the fence sections resulting from the 300 m scale (a.), it is very likely that these short fence could be easily sidestepped by the animals, and that the more efficient configuration, despite the lower number of roadkill events within it, is the one created by the coarser scale (b.).

Since the analysis can be run at a large number of scales, through a tailored design it is possible to identify a balance between the primary mortality reduction (the reduction of road mortality obtained by assuming that the animals within the fenced area would be prevented completely) and the probability of fence success (*probability that the roadkill within the fence are actually prevented by its implementation*), and detect the scale that would result in the most efficient configuration of fencing, short enough to prioritize higher roadkill aggregations, but still long enough to guarantee a high probability of success.

These two variables can be combined in the same analysis through an algebraic multiplication to obtain a revised mortality reduction that takes into account the presence of the fence-end effect and consequently predicts a more realistic mortality reduction that each configuration of fence would produce:

$$\textbf{Revised}\ \boldsymbol{mortality\ reduction = Primary\ mortality\ reduction * Probability\ of\ fence\ success}$$

The primary mortality reduction has therefore been evaluated at 4 different scales (300 m, 500 m, 1000 m, and 2000 m). For reasons of consistency and because fences are added in amounts of a certain minimum length (e.g., 100 m), we used a moving window approach and divided the road into 100 m segments, using the same length of road segments for all scales ("refined analysis" according to Spanowicz et al., subm).

The probability of fence success has been evaluated starting from a model that predict the fence-end effect as a function of length sections and home range size of the species (Jochen A.G. Jaeger, Stefano Re, 2019)

3.2.6 Primary mortality reduction and prioritization of the road segments

Based on the hotspot intensity values it is possible to identify the road segments in which the implementation of a fence would lead to a stronger primary mortality reduction. To prioritize the road segments, the following tasks were performed for each scale.

3.2.6.1 Steps done in Excel before using R

- An "ID" column is then made starting with "1" from the first road segment to the last.
- In Excel, based on the output data from Siriema, a "Rank" column is added, starting with a values of "1" from the highest *HS* (hotspot aggregation value) to the lowest. If this is an "even case", additional data need to be copied and pasted as explained below (see section on "Even case").
- On another sheet in the same Excel file, two columns are needed: one with an ID and another with the corresponding mortality amount for every road segment.
- The data is now ready for running the R script.

Another analysis is done to include the amount of road mortality for every road segment, where the radius is equal to the road segment length. The roadkill numbers in each segment are determined by adding *HS+Hsr* (in Excel the *HSr* value is called “Ksmed”). We implemented these steps in Excel, distinguishing two situations:

Odd case (a): if the scale of analysis is an odd multiple of the length of the road segment, e.g., 300 m, 500 m, the fence will always cover complete segments neighboring the road segments of highest rank that are identified (Tab. 4), and to detect the number of roadkill within it, information is needed about the amount of road mortality for every 100 m of road.

Even case (b): the scale of analysis is an even multiple of the length of the road segment, e.g., 1000 m, 2000 m, the fence will cover only 50% of the outer road segments neighboring the road segments of highest rank that are identified (Tab. 5), and to detect the number of roadkill within it, information is needed about the amount of road mortality for every 50 m of road.

Table 4: Example of an Excel file used in the odd case

ID	Rank	Distance (km)	Latitude	Longitude	HS	UCL	LCL	Hs(r)
1	537	0.05	47.113	-71.33	-2.167	2.326	-2.167	3.665
2	554	0.151	47.114	-71.33	-2.641	1.3587	-1.641	3.641
3	539	0.251	47.114	-71.33	-2.608	1.391	-1.608	3.608
…	…	…	…	…	…	…	…	…
685	666	68.845	47.649	-71.23	-3.667	2.323	-2.17	3.667

Table 5: Example of an Excel file used in the even case

ID	Rank	Distance (km)	Latitude	Longitude	HS	UCL	LCL	Hs(r)
1	531	0.05	47.113	-71.33	-4.473	6.951	-6.377	12.09
2	546	0.151	47.114	-71.33	-3.381	5.307	-5.118	12.07
3	533	0.251	47.114	-71.33	-2.475	5.515	-5.671	12.064
…	…	…	…	…	…	…	…	…
685	657	68.845	47.649	-71.23	-12.28	6.757	-6.571	12.284

3.2.6.2 Steps done in R

Once the R code is opened, it needs to be adjusted to the appropriate scale and road segment length used. The files can then be uploaded, and the R code can be run.

- The R code identifies the road segment that has the highest rank and identifies the first set of road segments that need to be fenced, including the segments next to the one of highest rank (e.g., the two next segments on either side if the scale is 500 m and the road segment length 100 m).
- Then the second highest ranked road segment is identified and the set of road segments that need to be fenced. If these new road segments overlap with segments that have already been determined for fencing, only the additional road segments will be identified.
- These steps are continued with lower and lower ranks until the entire road has been fenced. The result is a excel file in which is possible visualize for each rank of fence the percentage of mortality obtained (Table 6).
-

Table 6: Example of output of R for a 300 m scale.

ID	Rank fence	Fenc Stak2	M1	M2	M3	Sum mort	Len fence	Perc mort	Perc mort sum	Perc mort calc
369	2	36900	8.998	12.997	12.994	34.988	700	1.4	3.12	96.88
370	2	37000	0.000	0.000	9.995	9.995	0	0.4	3.12	96.88
209	2	20900	10.000	13.000	10.000	33.000	0	1.3	3.12	96.88
283	4	28300	8.000	11.996	10.995	30.990	300	1.2	1.24	95.64
284	6	28400	0.000	0.000	7.991	7.991	700	0.3	2.59	93.05
660	6	66000	8.994	10.995	7.999	27.988	0	1.1	2.59	93.05
319	6	31900	8.969	10.958	8.956	28.883	0	1.2	2.59	93.05

3.2.6.3 Results of the prioritization

To analyze the differences in the differences in the primary mortality reduction that the implementation of each section of fence would produce, we represented in the same graph the results of the prioritization according to the different scales. The abscises show total fence length and the ordinate indicates the primary mortality reduction obtained from the implementation of the fence, creating a primary mortality reduction graph that points out the differences in the number of roadkill prevented among the scales (see Fig. 9 in Results for an example). To visualize the reasons for these differences and fully understand the effects that varying scales produce in the configuration of fencing, we compared a same amount of fence (20 km) created by the four different scale (Fig. 10 in Results) and we highlighted the number and the average length of the sections created by the different scales (Table 7 in Results).

3.2.7 Probability of fence success and second research question

To our knowledge, only one study so far analyzed the reduction in WVCs by fencing road sections of differing length (Fig.6 ; Huijser et al. 2016). The results showed road sections with relatively long and contiguous wildlife fencing (at least 5 km long) reduced collisions with large mammals by 84.1% on average, while relatively short road sections with wildlife fencing (shorter than 5 km) reduced these collisions by 52.7% and and presented a far more variable effectiveness. (Huijser et al. 2016)

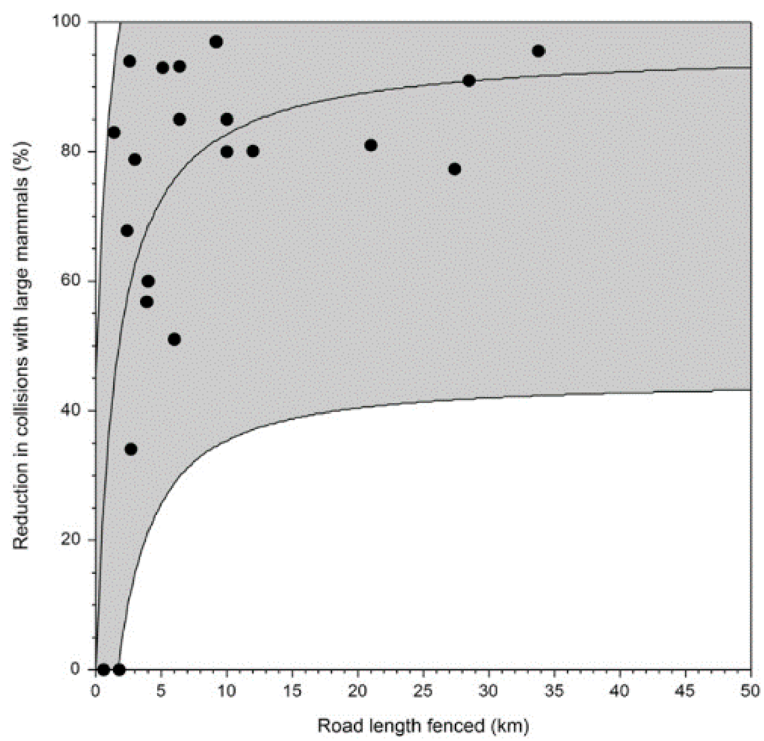

Figure 6: The effectiveness of 21 mitigated road sections of varying fence lengths in reducing collisions with large mammals. A Michaelis–Menten function (black line) was fitted to the data (Y = 96.07 ∗ X / (1.62 + X)) with associated 95% confidence interval (gray area) (source: Huijser et al. 2016).

Although the graph shown in Fig. 6 depends on the size of the home range of the species, its general shape depends mostly on the spatial configuration of WVCs and the fence length. Even if home range size varies, the shape of the graph remains similar. There always is an area in which great changes in fence length are associated with great changes in the probability of success and an area in which great changes in fence length are associated with low changes in the probability of success (for long fences). Identifying the fence length corresponding to the threshold between these two areas would be key for understanding which range of scales that would maximize the benefits of fencing.

While for scales finer than this threshold, increasing the scale would strongly increase the probability of fence success and moderately decrease the number of roadkill enclosed within the fence (and therefore generate benefits), after this point the gains in the probability of success would be lower, so that they may not be able to counterbalance the reduction in the number of animals enclosed (and therefore generate disadvantages). The most efficient length of fence can be identified by analyzing simultaneously how the two variables change with scale.

To estimate the probability of success of a fence, we created a model to predict the fence-end effect as a function of the home range size of the species. In particular, we assumed that for the animals for which their home range overlaps with the fence end, the probability that the fence will prevent them from entering the road is less than 100 %. Based on the integration of three different cases, the estimated probability of success of the fence of a particular length (L) is:

$$(1) \qquad P_{\text{success}} = \begin{cases} \frac{L^2}{6R^2} & if\ L < R, \\ 2 + \frac{7L^2}{12R^2} - \frac{7L}{4R} - \frac{2R}{3L} & if\ R \leq L \leq 2R \\ 1 - \frac{R}{L} & if\ L > 2R \end{cases}$$

where L = Length of the fence, and R = radius of the home range of the species considered. Using this model for each section of fence installed, it is possible to estimate the probability of success that the animals within these sections are actually prevented from accessing the road. The algebraic multiplication of this probability with the primary mortality reduction results in a revised mortality reduction graph that predicts a more realistic efficiency of the configuration of fence.

We analyzed the four configurations presented previously (total length of 20 km) considering as species the North American porcupine (R = 455 m). Starting from the number of roadkill within each section of fence and their probability of success we estimated the number of roadkill prevented by the implementation of each section of fence (Table 9 in Results). We then presented them in percentage as “revised mortality reduction” and we compared the result of each scale to identify the one that produces the highest benefits (Table 10 in Results).

To fully answer the second research question we applied the same procedure every 10 km (10 km, 20 km, 30 km, 40 km, 50 km, 60 km, 68.5 km) and plotted the revised mortality reduction graphs corresponding to the 28 configurations (4 scales, 7 total amounts of fence; Fig. 11 in Results).

3.2.8 Combining information from several scales

The most effective mitigation intervention can be determined only with a clear understanding of the spatial configuration of roadkill, and consequently, should be a synthesis of various scales of analysis. In particular, the sections of fence implemented by the coarse scales can be integrated with the additional information given by the analysis at finer scales to assess visually if their extension is consistent with the roadkill clusters along the road. This additional information could reveal that the distance between the end of the sections of fence implemented and the hotspot detected at a finer scale is particularly large or particularly short, which would allow for modifications to the fence length that could bring a higher reduction of mortality. To show the limitations of using a single scale analysis, Fig. 7 presents three fenced sections of road resulting from the analysis at 2000 m scale, with a 99% confidence level, and we determined with a hotspot analysis at 300 m scale where the corresponding roadkill aggregations are located.

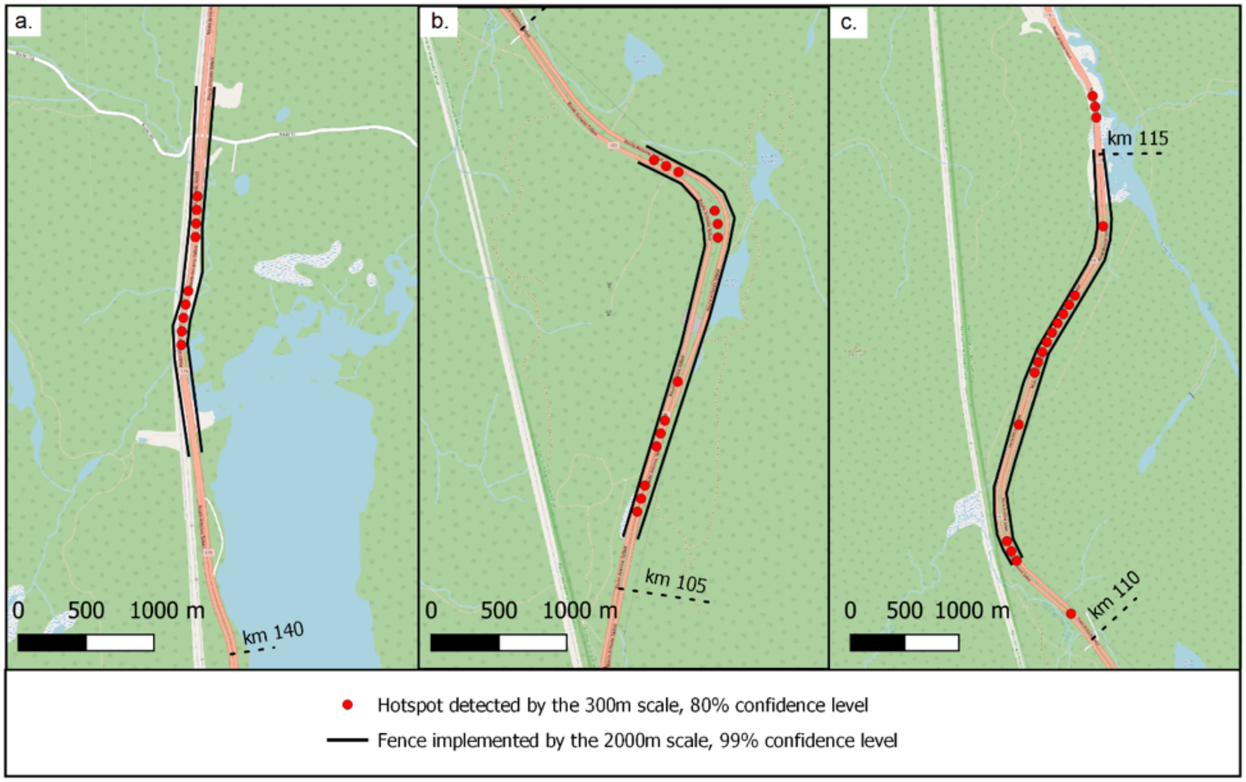

Figure 7: Three examples of fenced road sections resulting from an analysis at 2000 m scale, with 99% confidence level, and hotspot analysis at 80% of confidence level: (a) between km 140 and 145, (b) between km 105 and 110, and (c) between km 110 and 115. While some fence sections created by the coarse scale extend the length of the fence unnecessarily far from the regions with highest density of roadkill (a), others locate the end of the fence too close (b) or even just before them (c).

The hotspots identified at 300 m scale reveal the limitations of a single-scale analysis approach. Despite the great total length of the fence provided by the 2000 m scale analysis, the roadkill locations within the fence are not always far enough from the fence end to avoid a fence-end effect. While some sections of fence created by the large scale extend the length of the fence unnecessarily far from the regions with highest roadkill density (Fig. 7a), others locate the end of the fence too close (b) or even just before them (c).

Through the hotspots analysis at finer scales, is it possible to identify fenced sections that, despite their relatively great length, still present a high risk of a fence-end effect, and provide information about adjusting the amount of additional fence. In particular, it is possible to identify three situations in which a slight modification of the extension of fence can produce great benefits:

- Local cluster within the fence too far from the end (Fig. 7a): Since the majority of the animals is already at a great distance from the end of the fence, a reduction of the fence would bring a considerable increment in the theoretical mortality reduction without compromising the probability of success of the section.

- Local cluster within the fence too close to the fence end (Fig. 7b): Since a great amount of animals is situated close to the end of the fence, an extension of it would bring a considerable increment in the probability of fence success, because it would move these away from the end of the fence.

- Local cluster located just outside the fence end (Fig. 7c): Since the hotspot is immediately after the end of the fence, his extension would produce a double benefit: One in the primary mortality reduction (since a few hundred meters of additional fence would enclose numerous roadkill locations) and one in the probability of success of the fence (since the sections would be longer, and the roadkill within would be even farther from the end of the fence).

By varying the scales and confidence levels, it is possible to gradually fence different sections along the road and consider not only their priority but also the spatial roadkill configuration within them. The result will be configurations of fencing that always leads to a mortality reduction higher than the one based on a single scale.

3.2.9 Combining multiple scales and considering the presence of wildlife crossing structures

For this part of our study, we developed an analytical framework for prioritizing road sections for wildlife fencing based on the combination of the scales. We used two coarse scales (1000 m and 2000 m) to create continuous sections of fence, and we used a fine scale (300 m) to modify their length.

The analyses run in Siriema were the following:

- 2000 m scale, with two confidence levels (99% and 90%),
- 1000 m scale, with two confidence levels (99% and 90%),
- 300 m scale, with one confidence level (80%).

The Adaptive Fence Implementation Plan combine the information provided by these different scales and the ones regarded the wildlife crossing structures in the area to create configurations of fencing that are predicted to maximize mortality reduction.

This method can be seen as an iterative process composed of many cycles, in which each of it identifies new regions of the road to be fenced and implement sections of fence. If the regions identified are close to existing sections of fence, these are covered enlarging the existing fence, while if the regions identified are far from the existing fence, these are covered through the implementation of new sections of fence.

To perform the calculations, the results from Siriema were transferred into Excel, and a unique sheet was created. Roadkill data and the locations of existing wildlife passages and the fences associated with them are uploaded in GIS, (Fig.8a), and the cycle, composed by three steps (b, c, d), is applied:

a)
b) The sections of fence implemented by the analysis with the coarser scale with a higher confidence level and the hotspots determined at the finer scale are uploaded in GIS.
c) The length of the fenced section uploaded is adjusted until to entirely cover the outermost aggregation of roadkill detected as a hotspot by the fine scale and provide to them an adequate distance from the end of the fence. The amount of additional fence should be chosen according to a consideration of the home range of the species in analysis. In this case it was settled at 200 m. If a wildlife crossing structure is present within the fence, the section of fence should be extended at least until it.
d) In case the ends of the fence are at a distance less than 500 m from an existing wildlife crossing structure, or from another existing fence, the gap between them will be closed. Since the distance between the fence end the fence end of the wildlife passage in the example is 450 m the fence is extended, and the two fences are joined.

Fig. 8e shows the section of fence implemented by the first cycle, and the spatial configuration of roadkill within it. The outermost aggregation of roadkill within the section are now settled close to a wildlife crossing structure (km 110) or at least 200 m from the end (km 115);

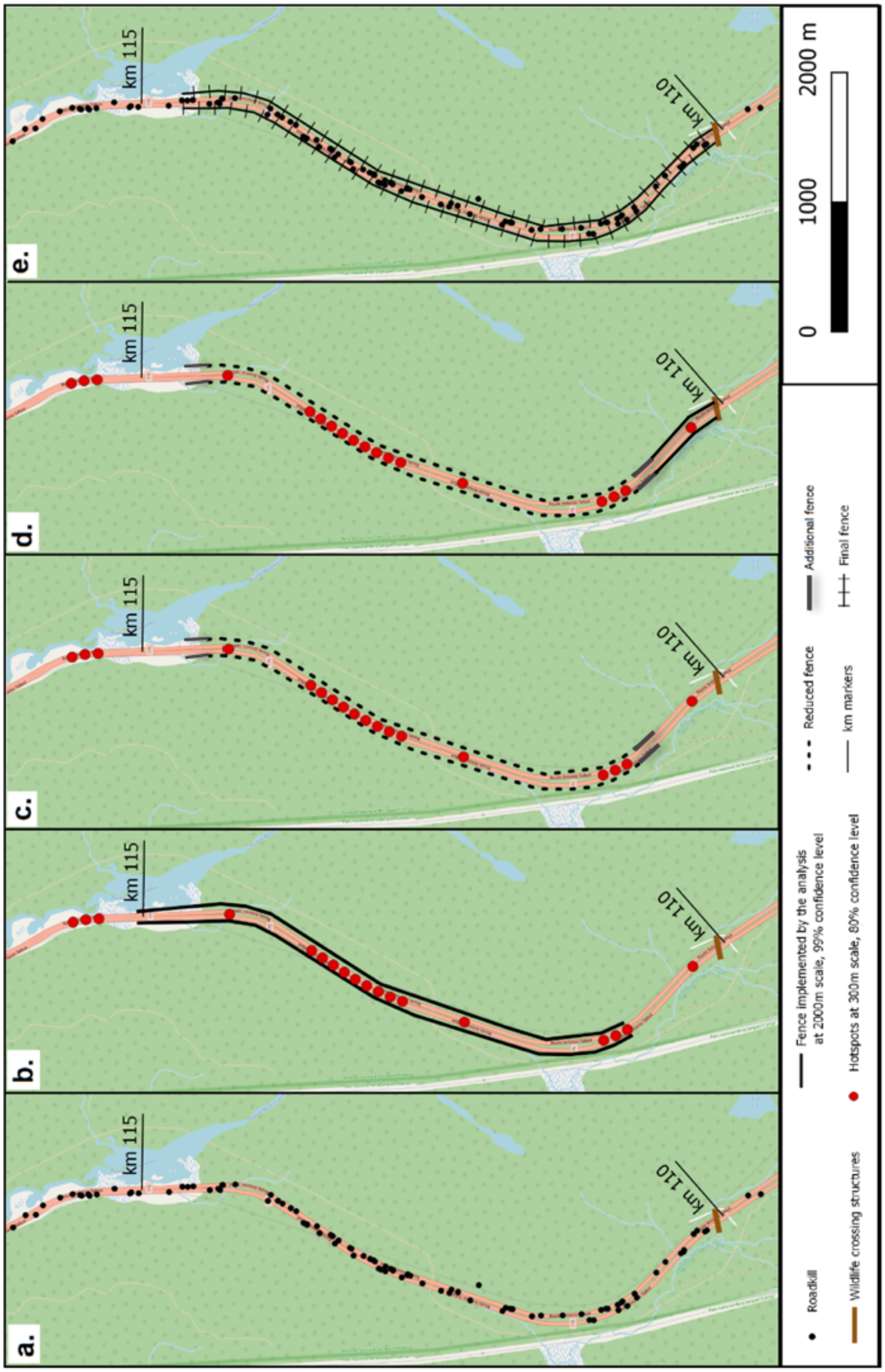

Figure 8: Illustration of the procedure applied to a section of fence that was identified by the hotspot analysis at 2000 m scale, using 99% of confidence level between km 110 and 115.
(a)Roadkill data, wildlife crossing structures and existing fences along the road
(b) Sections of fence implemented by the 2000m scale analysis and hotspot detected at 300m scale
(c) adjustment of the section of fence according to the information given by the finer scale
(d) extension of the fence due to the presence of the wildlife crossing structure
and (e) final section of fence identified by the method and roadkill data along the road.

Once the sections of fence related to the first cycle are implemented, the cycle (steps b,c,d) can be repeated at the finer scale and with the same confidence level, and new sections of fence (which are less extended, and consequently were not detected at the previous scale) are identified and added to the existing configuration.
Once all the scales have been considered with the highest confidence level, the cycle is repeated with a lower confidence level, and new sections of fence (which are less dense, and consequently were not detected at the previous confidence levels) are identified and added to the existing configuration.

The results of the analysis with lower confidence may identify new hotspots that were not previously detected. This will lead to a prolongation of the sections to be fenced identified so far.

3.3 Results

3.3.1 Effects of varying the scale of analysis and estimated mortality reduction without considering the fence end effect

The primary mortality reduction obtained (Fig. 9) and the configuration of fencing implemented (Fig. 10) vary greatly according to the scale used in the analysis.
The influence of the scale on the reduction of road mortality is represented in Fig. 9.
The primary mortality reduction of the four scales is compared in a graph that represents in the abscises the total fence length and in the ordinate the reduction that the implementation of each scale would produce not considering the presence of the fence end effect (assuming that all animals that encounter the fence are prevented from entering the road).
For any length, the smaller the scale used for the analysis, the greater the number of events enclosed within the sections of fence. For example, following the black line, it is possible to see the influence of the choice of the scale for a same amount of length (20 km) corresponding to each of the four scales. The primary mortality reductions obtained with the four scale, from the smallest to the coarsest, are respectively 54.48%, 50,82%, 48,05%, and 45.15%. For this length of potential fencing, the configuration of fence implemented by the smallest scale (300m) encloses approximately 9% more roadkill than the configuration of

fence implemented by the coarsest scale (2000m). Similar values are presented for other lengths of potential fencing.

The Influence of the scale on the length of the sections of fence implemented is represented in Fig. 10 and Table 7;

Fig. 10 shows a same amount of length (20 km) corresponding to each of the four scales. From this, it is possible to visualize that the length of the sections of fence implemented is proportional to the length of the scale used for the analysis. The finest scales (300m) detect only the most closely aggregated roadkill patterns and consequently result in a fragmentized configuration of fence, that presents the highest number of sections (34). Increasing the scale used for the analysis, the number of sections gradually decrease, until to reach the configuration created by the coarsest scale (2000m), in which half of these aggregations of roadkill is not anymore detected, and the other half is fenced with only 6 long and continuous sections of fence.

Table 7 presents, from north to south, the number and the length of the sections of fence implemented by the four scales. The number of the sections created by the 300, 500, 1000 and 2000m scales is respectively 34, 18, 8 and 6;

When the boxes below the 500, 1000 and 2000m scales are marked with " - ", it means that the hotspots that were previously identified by the 300 m scale are not anymore detected by the coarser scale (and therefore not anymore fenced), while when these present a greater size, it means that two or more hotspots that were previously detected by the 300m scale are now detected as a unique hotspot by the coarser scale (and therefore fenced with a continuous section of fence).

Table 8 resumes the effect of varying the scale of analysis on the primary mortality reduction and on the number and length of the sections of fence implemented;

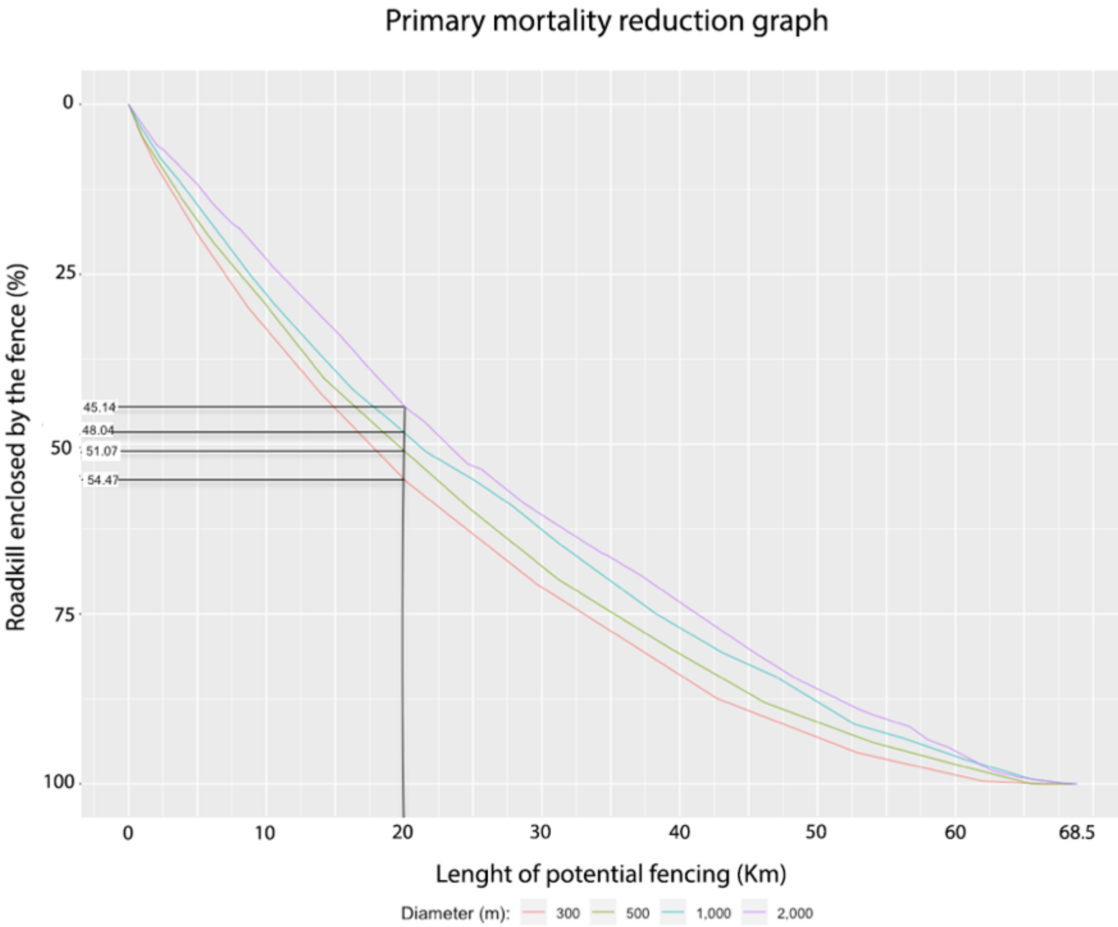

Figure 9: Primary mortality reduction graphs corresponding to four scales. The respected mortality reduction resulting from the implementation of a fence length of 20 km are indicated.

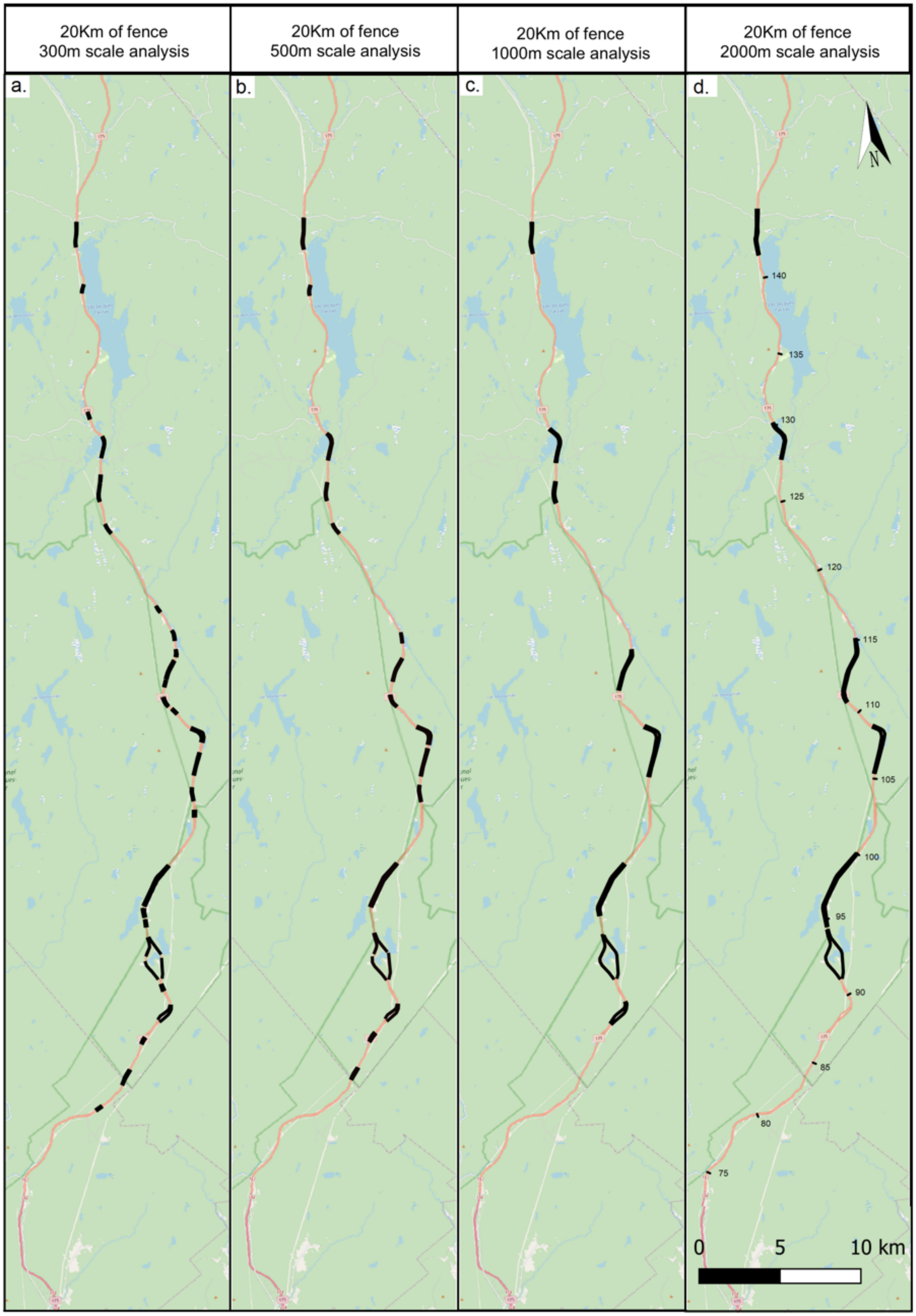

Figure 10: Implementation of fencing length of 20 km along the entire HWY 175 (km 75.5 – 143.5) according to a hotspot analysis at four scales (300 m , 500 m, 1000 m, 2000 m).

Table 7: Length of the sections of fence implemented by the 4 scales in analysis using a total fence length of 20 km.

<table>
<tr><th colspan="4">Length of the sections of fence [m]</th></tr>
<tr><th>300 m scale</th><th>500 m scale</th><th>1000 m scale</th><th>2000 m scale</th></tr>
<tr><td>600</td><td rowspan="2">1800</td><td rowspan="2">1900</td><td rowspan="2">2700</td></tr>
<tr><td>700</td></tr>
<tr><td>400</td><td>500</td><td>-</td><td>-</td></tr>
<tr><td>300</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>1200</td><td>1600</td><td>2200</td><td>2100</td></tr>
<tr><td>300</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>1000</td><td>1000</td><td>1200</td><td>-</td></tr>
<tr><td>500</td><td>600</td><td>-</td><td>-</td></tr>
<tr><td>300</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>500</td><td>500</td><td>-</td><td>-</td></tr>
<tr><td>300</td><td>-</td><td rowspan="3">2500</td><td rowspan="4">3900</td></tr>
<tr><td>1100</td><td>1400</td></tr>
<tr><td>300</td><td>-</td></tr>
<tr><td>500</td><td>700</td><td>-</td></tr>
<tr><td>300</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>1100</td><td>1400</td><td rowspan="2">3500</td><td rowspan="2">3000</td></tr>
<tr><td>1300</td><td>1600</td></tr>
<tr><td>700</td><td>900</td><td>-</td><td>-</td></tr>
<tr><td>300</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>500</td><td>600</td><td rowspan="5">4100</td><td rowspan="6">5200</td></tr>
<tr><td>800</td><td rowspan="3">2300</td></tr>
<tr><td>400</td></tr>
<tr><td>900</td></tr>
<tr><td>400</td><td>-</td></tr>
<tr><td>300</td><td>-</td><td>-</td></tr>
<tr><td>1100</td><td>1200</td><td rowspan="3">3000</td><td rowspan="3">3100</td></tr>
<tr><td>500</td><td rowspan="2">1600</td></tr>
<tr><td>600</td></tr>
<tr><td>300</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>1100</td><td>1100</td><td>1600</td><td>-</td></tr>
<tr><td>300</td><td>500</td><td>-</td><td>-</td></tr>
<tr><td>500</td><td>700</td><td>-</td><td>-</td></tr>
<tr><td>300</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>300</td><td>-</td><td>-</td><td>-</td></tr>
</table>

Table 8: Number and average length of the sections of fence implemented by the 4 scales in analysis using a total fence length of 20 km (as in Fig. 11), and primary mortality reduction obtained by their implementation.

	Scale			
	300 m	500 m	1000 m	2000 m
Number of sections to be fenced	34	18	8	6
Average length of sections to be fenced [m]	588	1111	2500	3333
Primary mortality reduction	54.48%	50,82%	48.05%	45.15%

3.3.2 Probability of fence success and estimated mortality reduction while considering the fence end effect

The estimated number of animals prevented by the implementation of the fence varies widely while considering the presence of the fence end effect.

Table 9 represents, for each section of fence installed by the different scales, the length of the section, the probability of success of the section (calculated using the probabilistic model), the number of roadkill within the section, and the estimated number of roadkill within the sections that are actually prevented by the implementation of the fence. While the sections resulting from the 2000 m scale analysis are long enough to guarantee a good probability of success, and the number of roadkill prevented by the implementation of the section of fence do not differ considerably from the number of roadkill within the sections, the same is not the case for the sections resulting from the finest scale. Most of the sections created by the 300m scale present a probability of fence success that range between 7,24 and 20,11%, and result consequently completely inefficient at reducing road mortality.

The primary mortality reduction, the probability of success of the configuration of fence and the revised mortality reduction of the four configurations have been represented in table 10; From this it is possible to see that, for the finest scales, the revised mortality reduction widely differs from the primary mortality reduction.

For example, the finest scale in the analysis, despite the greatest primary mortality reduction (54.47%), presents a very low probability of success (24.15%), which results in the lowest revised mortality reduction (19.17%); the number of roadkill prevented by the implementation of this configuration would be so low to compromise the entire mitigation plan.

Increasing the scale used for the analysis the probability of success of the configuration of fence increase, and the discrepancy between primary and revised mortality reduction diminish. The coarsest scale in the analysis (2000m), due to the great probability of success of the configuration of fence implemented (85.20%), presents primary and revised mortality reduction comparable (respectively 45.15% and 39.09%).

The highest revised mortality reduction is produced by the 1000m scale and 2000m scale (respectively 39.22% and 39.09%).

The revised mortality reduction of the four scales is compared in a graph that represents in the abscises the total fence length and in the ordinate the reduction that the implementation of each scale would produce, considering the presence of the fence end effect (Fig. 11;).

The purple line (2000 m scale) is almost always below the others, which means that the configurations created by this scale is predicted to prevent the highest number of roadkill.

Table 11 represents the result of the revised mortality reduction implemented by the different scales each 10km.

Table 9: Length of sections, probability of success, number of roadkill within the sections and predicted number of roadkill prevented by the four 20 km configurations, for each section of fence implemented.

Length of section of fence [m]				Probability of fence success				Number of roadkill within the sections				Number of roadkill prevented by the section of fence			
300 m scale	500 m scale	1000 m scale	2000 m scale	300 m scale	500 m scale	1000 m scale	2000 m scale	300 m scale	500 m scale	1000 m scale	2000 m scale	300 m scale	500 m scale	1000 m scale	2000 m scale
600	1800	1900	2700	20,11%	74,72%	76,05%	83,15%	13	36	34	40	3	27	26	33
700				25,50%				18				5			
400	500	-	-	12,94%	17,48%	-	-	6	10	-	-	1	2	-	-
300	-	-	-	7,24%	-	-	-	6	-	-	-	0	-	-	-
1200	1600	2200	2100	62,08%	71,56%	79,32%	78,33%	21	30	37	37	13	21	29	29
300	-	-	-	7,24%	-	-	-	6	-	-	-	0	-	-	-
1000	1000	1200	-	54,50%	54,50%	62,08%	-	22	22	23	-	12	12	14	-
500	600	-	-	17,48%	20,11%	-	-	10	10	-	-	2	2	-	-
300	-	-	-	7,24%	-	-	-	7	-	-	-	1	-	-	-
500	500	-	-	17,48%	17,48%	-	-	8	9	-	-	1	2	-	-
300	-	2500	3900	7,24%	-	81,80%	88,33%	6	-	53	72	0	-	43	64
1100	1400			58,64%	67,50%			30	34			18	23		
300	-			7,24%	-			6	-			0	-		
500	700	-		17,48%	25,50%	-		13	13	-		2	3	-	
300	-	-	-	7,24%	-	-	-	7	-	-	-	1	-	-	-
1100	1400	3500	3000	58,64%	67,50%	87,00%	84,83%	21	26	61	54	12	18	53	46
1300	1600			65,00%	71,56%			27	30			18	21		
700	900	-	-	25,50%	48,37%	-	-	16	18	-	-	4	9	-	-
300	-	-	-	7,24%	-	-	-	6	-	-	-	0	-	-	-
500	600	4100	5200	17,48%	20,11%	88,90%	91,25%	11	12	88	100	2	2	78	91
800	2300			34,72%	80,22%			18	56			6	45		
400				12,94%				9				1			
900				48,37%				25				12			
400	-			12,94%	-			9	-			1	-		
300	-	-		7,24%	-	-		6	-	-		0	-	-	
1100	1200	3000	3100	58,64%	62,08%	84,83%	85,32%	22	26	55	55	13	16	47	47
500	1600			17,48%	71,56%			9	25			2	21		
600				20,11%				15				3			
300	-	-	-	7,24%	-	-	-	7	-	-	-	1	-	-	-
1100	1100	1600	-	58,64%	58,64%	71,56%	-	25	25	30	-	15	15	21	-
300	500	-	-	7,24%	17,48%	-	-	6	11	-	-	0	2	-	-
500	700	-	-	17,48%	25,50%	-	-	9	10	-	-	2	3	-	-
300	-	-	-	7,24%	-	-	-	6	-	-	-	0	-	-	-
300	-	-	-	7,24%	-	-	-	6	-	-	-	0	-	-	-

Table 10: Primary mortality reduction, probability of success and revised mortality reduction produced by the configurations of fence length of 20 km generated by the four scales.

	scales			
	300 m	500 m	1000 m	2000 m
Primary mortality reduction	54,48%	50,82%	48,05%	45,15%
Probability of success of the configuration of fence	24,15%	48,44%	78,94%	85,20%
Revised mortality reduction	19,04%	30,77%	39,22%	39,09%

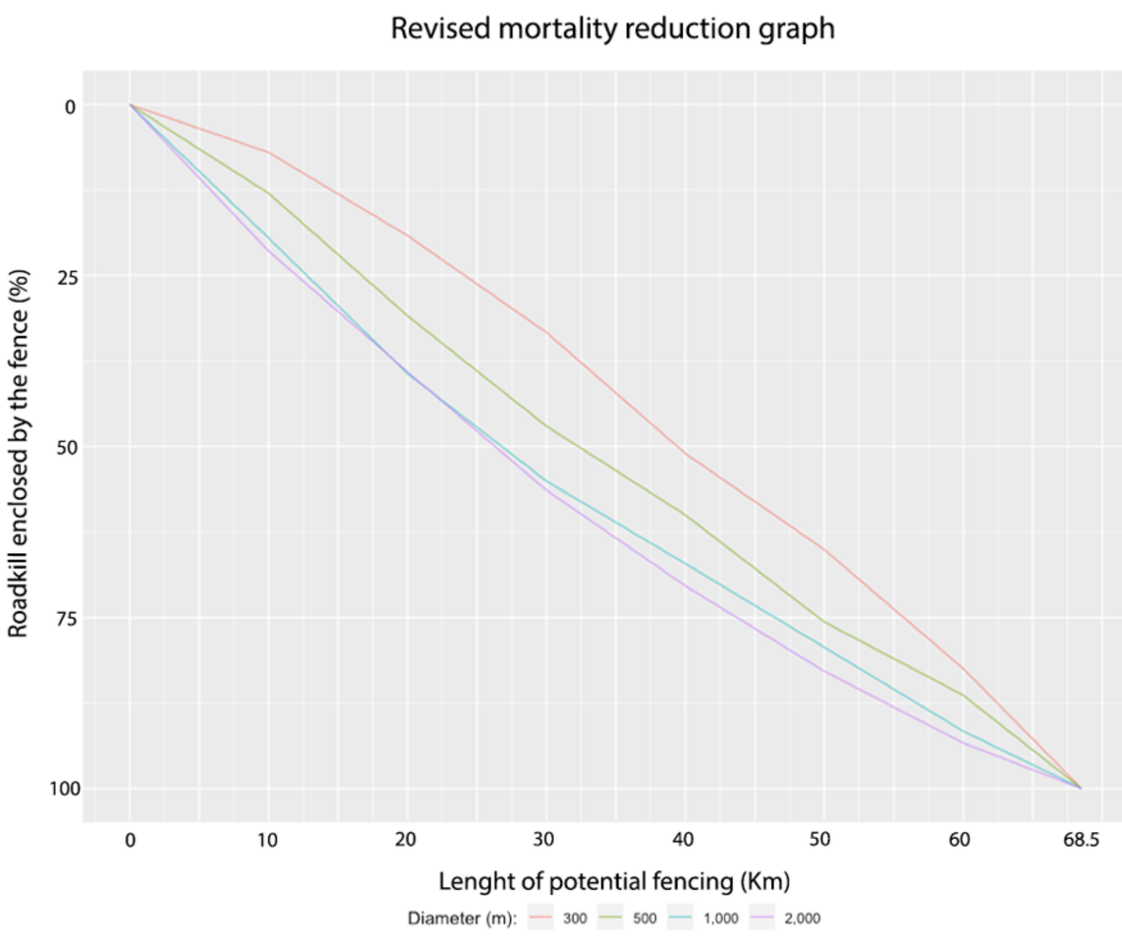

Figure 11: Revised mortality reduction produced by the different scales

Table 11: Revised mortality reduction produced by the configurations of fence generated by the different scales in different length

	0km	10km	20km	30km	40km	50km	60km	68,5km
300m scale	0%	7,01%	19,17%	33,33%	51,03%	65,08%	82,48%	100,00%
500m scale	0%	12,99%	30,89%	47,04%	60,03%	75,66%	86,38%	100,00%
1000m scale	0%	19,53%	39,34%	55,06%	67,14%	79,36%	91,63%	100,00%
2000m scale	0%	21,42%	39,09%	56,40%	70,38%	82,86%	93,36%	100,00%

3.3.3 Results of the scale-combination method:

The configurations of fence created by the scale-combination method are represented in table 12, and in Fig.12; each configuration of fence is the result of one cycle (step b,c,d, chapter 2.9);

- The first cycle (Fig.12a; Tab12 configuration1) identifies a configuration of fence of 19.8km that presents 5 sections which length ranges between 1800 and 7800m.
- The second cycle (Fig.12b; Tab12 configuration2) identifies two new hotspots far from the sections of fence implemented in the first configuration; as a result, two new sections of fence (1400m and 1800m) are implemented, and the total length of the configuration become 23.0km.
- The third cycle (Fig.12c; Tab12 configuration3) identifies new hotspots between the existing sections; as a result, the roadkill previously covered with sections two and three (2000 m and 1800m) are now fenced with a continuous section of 4600 m, and the ones previously covered with sections four and five (4600 m and 3600m) are now fenced with a continuous section of 10500 m. The total length of this configuration reaches therefore 26.1km.
- The last cycle (Fig.12d; Tab12 configuration4) identifies a new hotspot close km 105; as a result the section of fence of 10500m is further extended, up to cover a length of 12100m. The final configuration implemented presents 5 section of fence, which range between 1400 and 12100m and which total length is 27.7 km.

Besides the length of the sections of fence implemented, Table 12 present their probability of success, the number of roadkill within them and the estimated number of roadkill prevented by them. In this, it is possible to see that the probability of success of the sections of fence implemented ranges between 68% (for the shortest section, 1400m) and 96% (for the longest, 12100m).

The total length, the primary mortality reduction, the probability of success, and the revised mortality reduction of the 4 configurations implemented has been resumed in table 13.

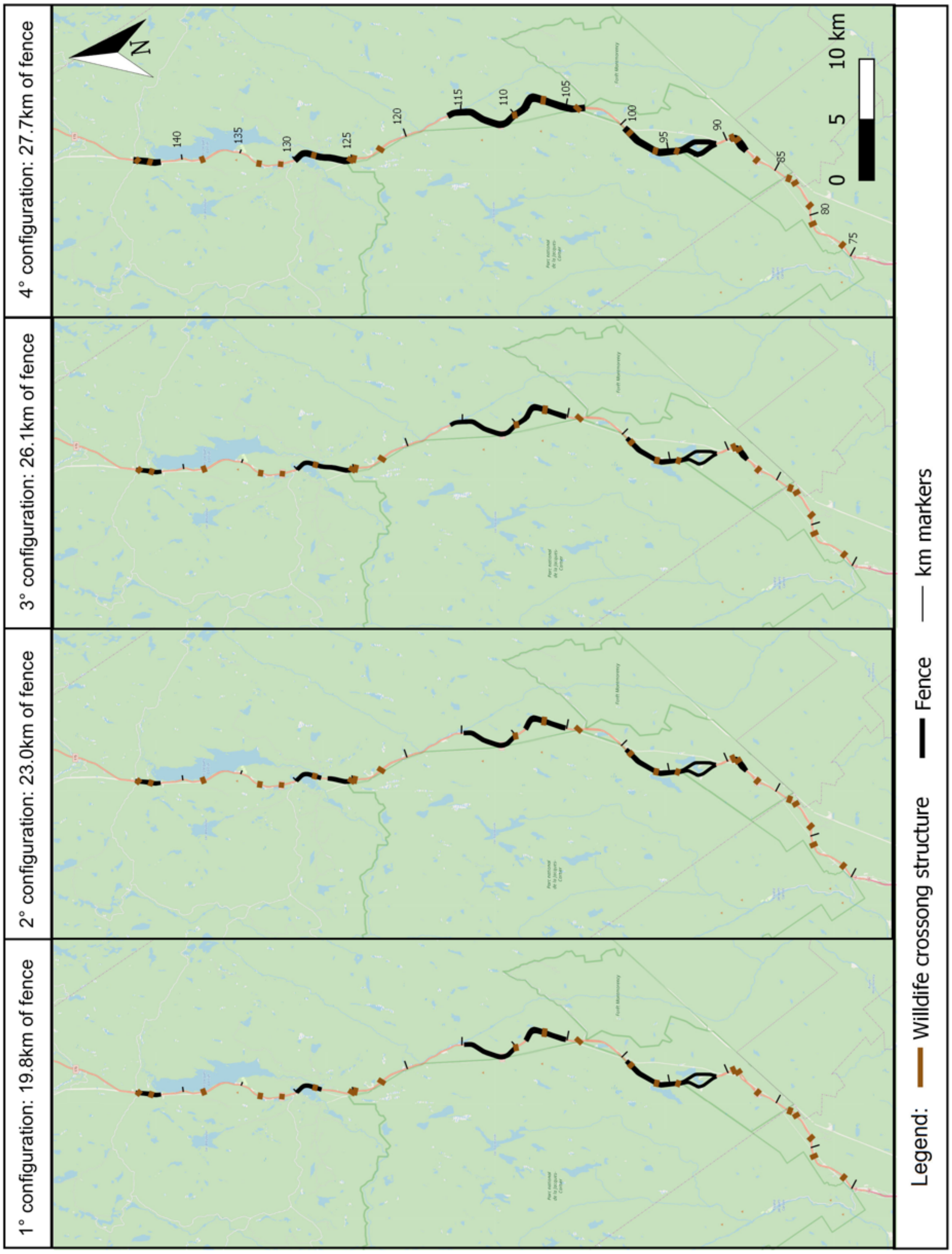

Figure 12: Four configurations of fencing along HWY 175, resulting from the combination of the scale in analysis and the consideration of the wildlife crossing structures, using 19.8 km, 23.0 km, 26.1 and 27.7 km of fence, respectively. each configuration of fence is the result of one cycle (step b,c,d, chapter 2.9) of the scale-combination method, and present sections of fence with low probability of fence end effect. Each section implemented by this method present at the sides or 200m of additional fence or a wildlife crossing structure, to get away the outermost hotspot from the fence end.

Table 12: Length of the sections of fence implemented by the scale-combination method and number of roadkill actually prevented.

Length of the section of fence				Probability of fence success				Number of roadkill within the sections				Estimated number of roadkill prevented by the section			
Config. 1	Config. 2	Config. 3	Config. 4	Config. 1	Config. 2	Config. 3	Config. 4	Config. 1	Config. 2	Config. 3	Config. 4	Config. 1	Config. 2	Config. 3	Config. 4
1800	1800	1800	1800	75%	75%	75%	75%	36	36	36	36	27	27	27	27
2000	2000	4600	4600	77%	77%	90%	90%	33	33	70	70	25	25	63	63
-	1800			-	75%			-	29			-	22		
4600	4600	10500	12100	90%	90%	96%	96%	82	82	166	186	74	74	159	179
3600	3600			87%	87%			61	61			53	53		
7800	7800	7800	7800	94%	94%	94%	94%	143	143	143	143	135	135	135	135
-	1400	1400	1400	-	68%	68%	68%	-	26	26	26	-	18	18	18

Table 13: Total length of fence [m], Primary mortality reduction and revised mortality reduction produced by the configurations of fence generated by the scale-combination method.

	Configuration 1	Configuration 2	Configuration 3	Configuration 4
Total length of fence [m]	19800	23000	26100	27700
Primary mortality reduction	44,77%	51,70%	55,61%	58,13%
Probability of success of the configuration	89%	86%	91%	91%
Revised mortality reduction	39,63%	44,64%	50,06%	53,11%

3.4. Discussion

3.4.1 Effects of varying the scale of analysis and estimated mortality reduction without considering the fence end effect

The scale in the analysis widely influences the number of roadkill detected by the hotspot analysis and the resulting configuration of fencing.

Ranking the clusters according to their level of significance, it is possible to prioritize the sections of fence with the highest rate of animal crossing and avoid a high amount of roadkill with the application of a few kilometers of fencing.

Assuming that all roadkill detected by the hotspot analysis would have been prevented by the implementation of the fence can be considered as an approximate guess of the mortality reduction generated by the implementation of the fence (Predicted primary mortality reduction); with this assumption, the smallest scale in the analysis is always the one that presents, a parity of length, the highest mortality reduction, since small scales can detect the most closely aggregated roadkill patterns, and consequently enclose a great number of roadkill with short sections of fence.

The choice of the scale influences also the length of the sections implemented. Analyzing the sections of fence implemented by the finest scale (300m) in Table 7, we see that these present an average length lower than the home range of most of the species in this study (588 m of average length, when the diameter of the home range of the target species is 910 m), and consequently, a high probability of fence end effect. Since the animals can easily move around the fence, very few of them would actually be saved by the fence, and the predicted primary mortality reduction is therefore very detached from reality. Increasing the scale, the length of the sections implemented increase, and the predicted primary mortality reduction better represent the real behavior of the fence. The sections resulting from the coarsest scale analysis (2000m) seem to be long enough to guarantee a good probability of success (3333 m of average length) and therefore their predicted mortality reduction may represent reality quite well.

To implement effective plans, and identify the scale that produces the highest benefits, it is necessary to take into account the presence of the fence-end effect and evaluate the scale in function of the home range of the species.

3.4.2 Probability of fence success and revised mortality reduction

The implementation of many short sections of fence may appear to be the more economical option but may not be as effective in reality, since the probability of a fence-end effect would be really high. In contrast, fewer longer fences may increase the likelihood that an animal moving along the fence will change course or use an existing wildlife passage before arriving at the fence-end and therefore reduce the probability of a fence-end effect, but their implementations would inevitably incorporate regions with a low density of wildlife crossings.

The use of a model that predicts the probability of success of the sections of fence implemented enabled an accurate estimation of the percentage of road mortality that would potentially be avoided with the implementation of the different configurations of fence. To estimate the probability of success of the sections of fence we used the porcupine (*Erethizon dorsatum*) as target species since its home range is approximately the average of the home ranges of the species in the analysis, and as it was the species most found dead on the road.

The revised mortality reduction obtained by 20km of fence implemented with the different scales (Table 10) revealed that the advantage of the finer scale (greater roadkill density enclosed within the fence) is completely canceled by the low probability of success of the short fence sections implemented, and configurations of fence generated by very small scales (300-500m), are therefore very ineffective at reducing road mortality.

The highest benefits are achieved when the scale used in the hotspot analysis ranges between 1000 and 2000m; the use of this range of scales generate configurations with sections of fence short enough to detect and prioritize high roadkill aggregations, but still long enough to have a good probability of success.

The results of this research question showed also that, for the species in analysis,

the scale of 1000 m seems to be the turning point (section 2.6). While below this threshold, increasing the scale produces a great benefit, since the increment in the probability of success of the configuration is more influential than the reduction in the density of roadkill enclosed, immediately after this point the influence of these two variables seems to be in balance. Until the 2000 m scale the revised mortality reduction produced is almost equal for any length (Fig. 11), which means that the reduction of roadkill detected by the coarser scale (2000m) is equally compensated by the increment of the probability of success of the sections.

When designing mitigation measures, our suggestion is to evaluate until where these variables are balanced and implement the configuration of fence produced by the coarsest scale. A parity of revised mortality reduction, in fact, coarser scales are preferable for the following reasons:

- Larger fenced road sections are apparently more effective as it incorporates more WVCs from different years. Over the years, the locations of the carcasses could vary, and when the fences are short, the mitigation measure would be less efficient.
- Longer fences could hold a higher number of roadkill locations together, and coupled with the implementation of crossing structures, would also result in higher connectivity, since more animals would be funneled towards them.
- The implementation of a few long sections of fence, a parity of total length, is cheaper than the implementation of many short sections.

To further increase the probability of success of the sections of fence implemented, the wildlife fence should be angled away from the road at a fence end (e.g. 45° or 90°). (Kruidering et al., 2005). This adjustment will not drastically increase the probability of success of the fence, but will increase the chance of get away from the road the animals that approach the fence end.

3.4.3 Benefits of the scale-combination method

The process of optimization also consider how the roadkill locations are distributed within the fence. For this reason the configurations created by the four cycles (Fig.12) presented a higher efficiency than the one obtained from a single-scale analysis.

The length of the sections of fence implemented, their probability of success, the number of roadkill within them and the estimated number of roadkill prevented by them are presented in table 12; in this it is possible to see that the length of the sections of fence implemented ranges between 1400 and 12100 m, and number of roadkill detected by them between 26 (for the shortest section) and 186. Their probability of success, calculated with the model, is respectively 68% and 96%, which mean that, in the shortest section, only 18 of the 26 roadkill detected are prevented by the implementation of the fence, and in the longest one, practically the entire number of roadkill detected (179) is prevented.

For consistency reasons, the probability of success is estimated with the same model used in the single-scale analysis; however, this model consider the events evenly distributed along the sections, and do not take into account that, in these configurations, all the roadkill aggregations within the sections created are at least 200 m from the end, and that many sections of fence funnel the animals to wildlife crossing structures; the effectiveness of the sections implemented is consequently higher than the one predicted in the table. For example, the probability of success of the shortest section of fence (1400m) implemented by the scale combination method is estimated to be the 68%, and consequently only 18 of the 26 roadkill within it are estimated to be prevented by its implementation; however, since the section present a wildlife crossing structure on one edge, and 200m of additional fence on the other edge, its probability of success is higher, and the number of roadkill prevented is therefore a value between 18 and 26.

Arguing along this line of reasoning, the estimated mortality reduction generated by each configuration is not anymore the revised mortality reduction, but it is a value between the revised and the primary mortality reduction, resumed in table 13.

The advantages of using the scale-combination method can therefore be assessed by comparing the estimated mortality reduction resulting from the 20km of fence implemented with a 2000m scale analysis and the one resulting from the 19.8km implemented with the scale-combination analysis. A parity of length, these configurations present the same revised mortality reduction (respectively 39.09% and 39.63%); the estimated number of roadkill prevented by the scale-combination method however tends to the primary mortality reduction (44,77%) since in reality almost all the roadkill within the sections of fence are prevented; all the sections implemented by the method present wildlife crossing structures or additional fence at the end, and consequently, contrary to the configuration produced by the single-scale analysis, also the outermost hotspot present a great chance of being prevented.

As represented in Table 13, thanks to the implementation of this method, it is possible to halve the number of wildlife-vehicle collisions fencing only 23 of the 68.5 km of road analyzed (33,6%).

The implementation of the fence for medium-sized mammals is typically 0.9-1.8 m high (Dorrance & Bourne, 1980; Robley et al., 2007; Rickenbach et al., 2011; Moreno-Opo et al., 2012; Smith et al., 2013), and since fencing for large-sized mammals are already present along major parts of the road, the new fence can be implemented on the poles of the existing fences. The cost of the new mitigation measure does not involve the cost of foundations, and it is consequently less expensive.

3.4.4 Limitations

Various road management handbooks suggest that the location of fence ends should coincide with some landscape features that would lead to a higher reduction of the probability of fence-end effect (Construction guideline for wildlife fencing, Huijser & al, Handbook of road ecology). Steep slopes (road cut or fill), river crossings, or areas with relatively high levels of human presence and disturbance are good examples of where one may choose to end a fence. Since the final aim of this paper was not the implementation of the fence in the study area, but the identification of an Adaptive Fence Implementation Plan, we didn't analyzed the topography of the area in implementing the four proposed configurations (Fig. 13); however, our suggestion is to evaluate if the topography present these features in close proximity to the fence end (a few hundred meters), and in case, modify the sections implemented with the scale-combination method, to further increase their probability of success.

To estimate the probability of the sections of fence implemented we used the porcupine (*Erethizon dorsatum*) as target species since its home range is approximately the average of the home ranges of the species in the analysis, and it was the species most found dead on the road. However, since the species that the fence should protect present a large range of home range sizes (from 1 ha to more than 4000 ha), and further research is needed to understand how to consider an average home range that better represent the animals in analysis.

Further research is also needed in order to identify the length of additional fence that should be applied to outdistance the outermost hotspots from the fence end. In particular, this distance could be better evaluated knowing how much the locations of local hotspots can vary over the years, and how do far animals move along the fence.

This information would be extremely useful for detecting the extension of the section that maximize even more the reduction of mortality.

3.5. Conclusions and recommendations

For the spatial pattern of roadkill along highway 175, we assessed the effects that the Hotspot analysis at different scales present on roadkill detection and on the configuration of proposed fencing. A parity of total length of fencing, we found that increasing the scale the number of roadkill detected decrease, while the length and the probability of success of the sections implemented increase. The degree with whom these variable change depends principally on the scale in analysis and on the home range of the species. Using a model that estimate the probability of success of the sections of fence we addressed the FLOMS trade-off, discovering that, to implement effective configurations of fence, the scale used for the hotspot analysis should be at least the size of the home range of the species living the area. Our results in fact shows that, considering an home range size of 910m, the first effective configuration of fence was produced by a scale of 1000 m. Configurations of fence identified with lower scale (300 and 500m), despite the great number of roadkill enclosed, resulted ineffective in reducing road mortality, since presented sections of fence that could be easily sidestepped by animals.

We further demonstrated that, in case of absence of data regarded the species in analysis, an overestimation of the scale is often preferable; while an underestimation of the scale in analysis would produce sections of fence completely inefficient due to the high risk of fence-end effect, and therefore not reducing road mortality, an overestimation of the scale in analysis would only slightly reduce the mortality reduction, without compromising the efficiency of the mitigation plan.

To identify how much the sections identified should be prolonged to prevent fence-end runs, we recommend to use various scales in the same analysis and to consider the location of wildlife crossing structures. The configurations of fence implemented through our Adaptive Fence Implementation Plan demonstrate that, in doing this, it is possible to maximize the mortality reduction and increase the connectivity among the regions.

4. Thesis conclusions

In this thesis we evaluated the efficiency of different configurations of wildlife fencing and develop an Adaptive Fence Implementation Plan that, in a cost-effective manner, identifies the configuration of fence that minimize the number of wildlife-vehicle collisions. In order to have a full comprehension of the problem and design an accurate solution, the work has been divided in three parts.

In the first part of this research, we evaluated the effects of changing scale in analysis on the proposed configuration of fencing, and the number of roadkill detected by the sections of fence implemented with the different scales. The results showed that these are widely influenced by the scale used in the analysis. The smallest scale in the analysis is always the one that creates, a parity of total length, the shortest sections of fence, and consequently, the one with the lowest probability of success. On the other hand, the smallest scale in analysis is also the one that detect the highest number of roadkill.

In the second part of this research we analyzed the probability of fence success creating a probabilistic model that predict the fence end effect starting from the home range of the species in analysis. Using this model, we estimated the effectiveness of the sections of fence implemented by the different scales, and we estimated the number of roadkill prevented by the implementation of different configurations of fence. The results obtained revealed that the choice of the scale in analysis widely influence the effectiveness of the fence, and demonstrated that, to identify sections of fence long enough to prevent the fence end effect, the scale in analysis should be at least as long as the home range of the species that the fence should prevent. Furthermore, we demonstrated that, when there is no knowledge of the home range of the species in analysis, an overestimation of the scale is preferable; while a too low scale would produce sections of fence completely inefficient due to the high risk of fence-end effect, a too coarse scale would only slightly reduce the mortality reduction, without compromising the efficiency of the mitigation plan. We however suggest, whenever is possible, to evaluate the mitigation measures in function of the species in analysis. Investigating the effectiveness of the proposed configurations provide a valuable tool for sustainable decision-making; the estimated mortality reduction generated by the proposed configurations can be in fact used in a cost-benefit analysis to determine all the potential costs and revenues of the fencing, and promote the approval of the mitigation project.

In the last part of our work, we combined the scales in analysis to have a better understanding of where wildlife-vehicle collisions could appear, and we integrated at these results other information related to the location of the existing wildlife crossing structure and the home ranges of the species in analysis. All this information were combined in an Adaptive Fence Implementation Plan that, for each cycle, identifies the locations in which wildlife fencing is more needed, and tailor the extension of the fence, creating sections that are not so long to waste fencing where there are few animal fatalities, and not so small to be easily sidestepped.

We believe that the result of this paper will be extremely useful to researchers and practitioners to formulate new approaches to road safety, wildlife management, road design. The configuration of fence identified by the Adaptive Fence Implementation Plan can be

personalized on the species to prevent, the characteristics of the study areas and the characteristics of the roadkill spatial pattern. In our case, we tailored the design on 4 cycles, and the results were 4 configuration of fence (19.8,23,26.1 and 27.7km) that are predicted to maximize the benefits of the fencing.
We recommend to implement one of these proposed configuration and execute a Before-after-control-impact (BACI) design, in order to evaluate the strength of the results and assess the efficacy of the proposed method, and enable future research that could reduce even more the number of wildlife-vehicle collisions.

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