No Light at the End of the Tunnel: Limited Mammal Use of Unmitigated Bridges and Large Water Culverts to Cross Under Roads in the Laurentides

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ABSTRACT

No Light at the End of the Tunnel: Limited Mammal Use of Unmitigated Bridges and Large Water Culverts to Cross Under Roads in the Laurentides

Valérie Bolduc

Roads are a barrier to mammal movement, yet wildlife passages are infrequently implemented. Alternatively, some species are reported crossing through more common road infrastructure such as bridges and water culverts. I aimed to better understand how mammals use these structures to connect their habitats by investigating potential predictors of their use. My research focused on the Laurentides region in Quebec, where two parallel major roads bisect every ecological corridor linking two national parks. From June 2022 to December 2023, I installed trail cameras to monitor mammals at two bridges and eight large box culverts and placed track boxes in the surrounding habitat for 20 concurrent weeks. Mammals associated with urban landscapes were the most prevalent among the 20 different species or groups of species identified across all sites, of which only 11 made at least one full crossing. Many species from the region were notably absent, particularly large mammals. Six species were often observed in water and were the only species who crossed through sites that had no continuous dry ledge. Minimum water depth to cross a site was the strongest predictor to deter mammals, as the sites with the highest water depths were rarely or never crossed even by water-tolerant species. Much greater bridge use shows that unmitigated culverts are largely unsuitable for mammal movement. I strongly recommend adding dry ledges or shelves to the structures to mitigate the roads’ impacts on connectivity, and wildlife fencing to prevent road mortality and guide animals to sites with these features.

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Contribution of Authors

As the first author, I was responsible for the study design, data collection, processing, analysis and interpretation, and the writing of both manuscripts. The manuscripts were co-authored by Marie-Lyne Després-Einspenner, who was responsible for partner coordination and revision of the French manuscript. The manuscripts were also co-authored by Dr. Jochen Jaeger, who advised on study design and data analysis, and revised both manuscripts. Both co-authors and I were responsible for project conception and applications for funding.

Table of contents

List of Figures xi

List of Tables xiii

List of Abbreviations xiv

1 Introduction 1

2 Literature Review 4

2.1 Overview of the ecological impacts of roads focused on mammals 4

2.1.1 The road 4

2.1.2 The verge 6

2.1.3 The road-effect zone 7

2.1.4 The barrier effect 8

2.1.5 Landscape fragmentation 9

2.2 Mitigation measures 10

2.2.1 Various types of mitigation measures 10

2.2.2 Wildlife passages and other structures 13

2.2.3 Wildlife passage characteristics 15

2.2.4 Known existing structure use near the study area 16

2.3 Road ecology in the Laurentides 17

2.3.1 A portrait of the Laurentides 17

2.3.2 Two major Laurentides roads 20

3 Manuscrit : Efficacité limitée des ponts et ponceaux non aménagés pour la connectivité des mammifères dans les Laurentides 24

3.1 Résumé 24

3.2 Titre et résumé anglais 25

3.3 Mise en contexte et objectifs 25

3.4 Méthodologie 29

3.5 Résultats et discussion 35

3.5.1 Utilisation des structures par les mammifères 35

3.5.2 Différences dans les caractéristiques physiques 40

3.5.2.1 Ponceaux ... 40
3.5.2.2 Ponts ... 42
3.5.3 Espèces peu ou jamais observées ... 43
3.6 Recommandations ... 44
3.7 Conclusion ... 45
4 Manuscript: Water Depth Deters Mammal Species from Crossing Unmitigated Bridges and Large Water Culverts Under Roads ... 47
4.1 Abstract ... 47
4.2 Introduction ... 48
4.2.1 Effects of roads on mammals and mitigation measures ... 48
4.2.2 Bridges and water culverts ... 49
4.2.3 Geographical context ... 50
4.3 Research questions ... 52
4.4 Methods ... 53
4.4.1 Site selection ... 53
4.4.2 Data collection and processing ... 55
4.4.2.1 Trail cameras ... 55
4.4.2.2 Track boxes ... 56
4.4.3 Statistical analysis ... 58
4.4.3.1 Overview of statistical approach ... 58
4.4.3.2 GLMM structure ... 59
4.4.3.2.1 Response ... 60
4.4.3.2.2 Monthly variation ... 60
4.4.3.2.3 Predictor variables ... 61
4.4.3.2.4 Offset ... 63
4.4.3.2.5 Family ... 63
4.4.3.2.6 Datasets ... 64
4.4.3.2.7 Track-paper particularities ... 64
4.4.3.3 Multimodel inference ... 65
4.4.3.4 Interaction GLMMs ... 65

4.5 Results 66
4.5.1 Mammal groups by water tolerance 66
4.5.1.1 Detections by groups 66
4.5.1.2 Site use 69
4.5.1.3 Temporal use 71
4.5.2 Influence of predictor variables 72
4.5.3 Small and medium-sized species nearby 78
4.6 Discussion 79
4.6.1 Groups and predictors 79
4.6.2 Species found in the surrounding habitat 82
4.6.3 Limitations 84
4.7 Conclusion and recommendations 85
5 Thesis Conclusion 89
6 References 93
7 Appendices 116
7.1 Nombre de détections par espèce, type de détection et site. 116
7.2 Translated French manuscript figures, table, and appendix 121
7.2.1 Map of the Laurentides: research sites, core conservation areas, ecological corridors and roads. 121
7.2.2 Photos of the research sites (B = bridge, C = culvert). 122
7.2.3 Geographic, physical, and environmental characteristics of each site. Annual average daily traffic (AADT) comes from (MTMD, 2023d). For the sites with two structures: data for height, width, and length are an average of the values for both structures. These values and the construction year were provided directly by the MTMD. Sites with two construction years are because the secondary structure was added at a later date. 123
7.2.4 Diagram of the camera layout on a site, aerial view. 124
7.2.5 Photos of the animals at the sites. From top to bottom, left column: American mink, stoat or weasel, squirrel, raccoons. Right column: red fox, white-tailed deer, raccoons, beaver. 125

7.2.6 Number of detections by species or group of species, all sites combined, according to the type of detection. 126

7.2.7 Number of detections and number of species by site, according to the type of detection. 127

7.2.8 Number of detections by species, type of detection, and site. 128

7.3 All detections by species group and minimum water depth to cross through per site. 132

7.4 All detections for four most often detected species overall and minimum water depth to cross through per site. 133

7.5 Predicted response of the spline by month for the global All-Species GLMM 134

7.6 GLMM(s) coefficients, variance, and significance as given by the summary function in R. Significance codes according to R: 0 < ‘***’ < 0.001 < ‘**’ < 0.01 < ‘*’ < 0.05 < ‘.’ < 0.1 < ‘ ’ < 1 135

List of Figures

Figure 3.3.1 Carte des Laurentides : sites de recherche, noyaux de conservation, corridors écologiques et routes 27

Figure 3.4.1 Photos des sites de recherche (B = pont [bridge], C = ponceau [culvert])......... 30

Figure 3.4.2 Schéma de la disposition des caméras sur un site, en vue aérienne 33

Figure 3.5.1 Photos des animaux sur les sites. De haut en bas, colonne de gauche : vison d'Amérique, belette ou hermine, écureuil, ratons laveurs. Colonne de droite : renard roux, cerf de Virginie, ratons laveurs, castor 36

Figure 3.5.2 Nombre de détections par espèce ou groupe d'espèces, tous sites confondus, selon le type de détection 37

Figure 3.5.3 Nombre de détections et nombre d'espèces par site, selon le type de détection 41

Figure 4.4.1 Overview of sites and mammal detections. (a) Road development over site C3 where A-15 and R-117 merge. (b) Camera placement. (c) Site C2. (d) Inside of site C3. (e) White-tailed deer in site B1. (f) Six raccoons with their paws in water in site C7.................. 54

Figure 4.4.2 Track-box data collection. (a) The inside of a track box. (b) A track box in its environment. (c) View of a groundhog inside of a track box. (d) A track-box ID and date (colloquial site name). (e) Domestic cat and groundhog tracks. (f) Mouse or vole tracks...... 57

Figure 4.5.1 Full crossings and inside detections by species group and minimum water depth to cross through per site... 70

Figure 4.5.2 Full crossings for four most often detected species overall and minimum water depth to cross through per site 71

Figure 4.5.3 Detections by species group (water-tolerant [without raccoon], raccoon, water-intolerant, low-detection) per month 72

Figure 4.5.4 Predicted response per month for the global GLMM with All-Species by coefficient with a 95% confidence interval in the shaded area. The track-paper coefficient used the global GLMM with species in track papers only (by month) 75

Figure 4.5.5 Predicted response per month for the global model with All-Species for the minimum water depth coefficient separated by species. The Y-axis is on the log scale. The species in the legend are listed in their respective order on the plot. “T” indicates a water-tolerant species, “I” indicates a water-intolerant species. 76

List of Tables

Tableau 3.4.1 Caractéristiques géographiques, physiques et environnementales de chaque site. Débit journalier moyen annuel (DJMA) provenant du MTMD (2023d). Pour les sites avec 2 structures : les données de hauteur, largeur et longueur sont une moyenne des valeurs des 2 structures 32

Table 4.4.1 Predictors used in GLMM analyses........ 62

Table 4.5.1 Mammal species observed at least once in the water with their detections on dry ground, in the water, or swimming........ 66

Table 4.5.2 Detections by water-tolerance group, species, and type of detection........ 68

Table 4.5.3 GLMM(s) coefficients with their significance and R^2. Averaged GLMMs use weighted marginal R^2 and weighted conditional R^2. Significance: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$ 73

Table 4.5.4 The total number of track papers with species presence recorded per two-week period, ordered by total number of track papers by species. Positive numbers in bold indicate that the species was not observed at the site by the cameras. Zeros in bold and underlined indicate that the species was observed at the site by cameras but not by track papers........ 79

List of Abbreviations

Abbreviations	English	French
A-15	Highway 15	Autoroute 15
AADT	Annual Average Daily Traffic	Débit journalier moyen annuel (DJMA)
AICc	Corrected Akaike Information Criterion	Critère d'information d'Akaike corrigé
ÉCL		Éco-corridors laurentiens
GLMMs	Generalised linear mixed models	Modèles linéaires généralisés mixtes
MELCCFP	Ministry of Environment, Fight Against Climate Change, Wildlife and Parks of Quebec	Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs du Québec
MRC	Regional county municipality	Municipalité régionale de comté
MTMD	Ministry of Transportation and Sustainable Mobility of Quebec	Ministère des Transports et de la Mobilité durable du Québec
R-117	117 Road	Route 117
WVC	Wildlife-vehicle collisions	Collisions fauniques

1 Introduction

Roads are responsible for a plethora of negative impacts on wildlife, the most visible being road mortality caused by wildlife-vehicle collisions (WVC) (Jaeger et al., 2005; Rytwinski & Fahrig, 2015; Seiler & Helldin, 2006). Wildlife is also greatly affected by landscape fragmentation caused by the road network and human development next to it. Amphibians, birds, insects, reptiles, and mammals are all impacted by roads, which can threaten population viability and lead some species to become locally extinct, impacting the rest of the ecosystem (Barrientos et al., 2021; Fahrig & Rytwinski, 2009; Jaeger et al., 2005). Reduced population abundances for mammals are observed over several kilometers perpendicularly to roads in the road-effect zone (Benítez-López et al., 2010; van der Ree et al., 2015). Additionally, mammals, and carnivores in particular, are disproportionately impacted by roads compared to other wildlife groups. Common characteristics of these species groups, such as large home ranges, requiring them to cross roads more frequently, and low reproductive rates, making it harder to replace individuals lost to WVC, place them at a disadvantage (Barrientos et al., 2021; Patterson, 2023; Rytwinski & Fahrig, 2012).

The most common effective mitigation measures to reduce WVC and increase wildlife movement are wildlife fencing and wildlife passages, which are often combined for a greater reduction of road impacts (Huijser et al., 2008; Rytwinski et al., 2016). The main drawback of these measures is their cost, limiting widescale implementation (Huijser et al., 2008; Raibaldi, 2020). Some animals have adapted to roads to some degree by going through other types of road infrastructure like bridges and water culverts instead of crossing over the pavement or not crossing at all. Although these structures are much more prevalent in the road network than wildlife passages, their capacity at promoting mammal movement has been much less studied compared to their purpose-built counterparts (Seiler & Olsson, 2010). As the impacts of roads on mammals are increasingly understood and considered by transportation agencies, systematically modifying existing and planned new bridges and water culverts could become an effective option to increase ecological connectivity across the road network.

The Laurentides region in Quebec, known for its two national parks and large natural areas, has been the victim of urban sprawl and landscape fragmentation in recent decades (Cole, Kross, et al., 2023; Després-Einspenner et al., 2020). These human developments are connected by Autoroute 15 (A-15) and Route 117 (R-117), which run parallel to each other and divide the entire region in two. Ecological corridor mapping, based on keystone species, their natural habitats, and anthropogenic barriers in the Laurentides, revealed that A-15 and R-117 bisect every ecological corridor linking Parc national de Mont-Tremblant to Parc national d'Oka (Després-Einspenner et al., 2020). Between the cities of St-Jérôme and Mont-Tremblant, spanning 75 km of road, no wildlife passages or fencing have been installed and only one defunct train underpass has been naturalised, despite large-mammal collisions on A-15 in this region costing over half a million dollars annually to Quebec taxpayers (Raibaldi, 2020).

A few studies and a report have investigated mammal use of bridges and water culverts in the Eastern Townships and in Vermont, regions close to the Laurentides (Brunen et al., 2020; Marangelo, 2019; Warnock-Juteau et al., 2022). This thesis sets itself apart by focusing mainly on large concrete box culverts, by selecting a different set of potential predictor variables focused on water, by performing model averaging on sets of generalised linear mixed models (GLMMs) to estimate predictor influence, and by comparing species found at the research sites to those found in the Laurentides. Moreover, this thesis includes the first road ecology project in the Laurentides which involved large-scale field data collection.

This thesis is divided into three parts. First, a literature review presents the state of knowledge in road ecology, mitigation measures, and the Laurentides region. Second, a French manuscript, published in *Le Naturaliste canadien*, gives a portrait of the situation aimed at a Quebec audience. It covers the following research objectives:

1. Characterise and evaluate the use by mammals of large existing structures under A-15 and R-117 in the Laurentides.

2. Identify differences in the use of large existing structures according to their physical characteristics.

3. Determine which mammal species present in the Laurentides do not use large existing structures.

Third, a follow-up English manuscript for an international audience focuses its more advanced statistical analysis on the relationships between mammals, water, and species present nearby, and addresses the following research questions:

1. Do water-tolerant mammal species differ from other species in their use of bridges and large water culverts to cross roads?

2. What predictors, in particular related to water, influence the use of bridges and large water culverts by mammals, and how do these differ by species or species groups?

3. Which small and medium mammal species are located near bridges and large water culverts and how are the species observed in the culverts and bridges related to the ones observed in their vicinity?

2 Literature Review

2.1 Overview of the ecological impacts of roads focused on mammals

2.1.1 The road

Habitat loss is the main pressure contributing to the global decline of biodiversity (Rands et al., 2010). Not only are roads directly responsible for habitat loss where they are located, but they also contribute to the degradation of habitats in their proximity (Ascensão et al., 2015; van der Ree et al., 2015). Large areas need to be paved to accommodate the road; this area is called the roadway. These following elements control the width of the roadway: the average annual daily traffic (AADT), the speed of the vehicles, the function of the road, which varies from small access road to major highway, the number of lanes, the lane width, the median width, and the shoulder width. The width dimensions presented here are focused on highways, because they normally have the largest roadway, and highways the focus in this thesis (Grilo et al., 2011). In the United States, the recommendation for highways is to have two paved lanes per direction, with a lane width of 3.6 m. Median width normally ranges from 1.2 m to 24 m but can be even greater. Larger median widths can be landscaped with trees and other vegetation. The shoulder, located next to the traffic lanes, should be 3 m wide for highways, and it should be either partially or fully paved (American Association of State Highway and Transportation Officials, 2018). In total, by adding these numbers, the recommended roadway width for highways in the United States ranges from 21.6 m to 44.4 m. The clear zone is an area meant for vehicles who veer from the traffic lanes, and as such, it should be cleared from obstructions such as trees (American Association of State Highway and Transportation Officials Technical Committee for Roadside Safety, 2011). This area includes the shoulder and the road verge, the latter being the strip of managed vegetation adjacent to the paved shoulder (Forman & Alexander, 1998). The recommended clear zone width for highways can be as high as 14 m based on slope and speed (American Association of State Highway and Transportation Officials Technical Committee for Roadside Safety, 2011). In summary, the width needed to accommodate a highway in the landscape requires a minimum of three dozen meters. This size represents the minimum distance between unmodified habitat patches. For forest dwelling species, this modification usually means the complete removal of habitat in this zone (Ascensão et al., 2015). Animals with small home ranges can also lose their entire habitat due to the landscape modifications needed for road building (Ascensão et al., 2015).

WVC are the most visible impact of roads on wildlife for the public (Seiler & Helldin, 2006). This road mortality is particularly important to transport authorities, because collisions with large mammals can result in serious harm to human health and incur major financial losses (Diarra et al., 2018; Huijser et al., 2009). Across the globe, billions of animals are killed by vehicles annually (Barrientos et al., 2021). On a continental scale, 29 million mammals of all sizes are estimated to die from WVC in Europe per year (Grilo et al., 2020). Using deer (*Odocoileus sp.*) as an example, in the United States, more than one million WVC occur with these ungulates annually (Conover et al., 1995). Deer are killed in 92 % of WVC (Allen & McCullough, 1976). In 2007, each deer collision also cost on average US$6,617 in the United States (Huijser et al., 2009). The proportion of deaths of mammals caused by WVC has increased in previous decades (Hill et al., 2019). In North America, 9.2 % of medium and large mammal deaths are attributed to WVC. This percentage is correlated with the human footprint index and can increase to 59 % in high areas (Collins & Kays, 2011). Although these overall mortality estimates seem high, they are extrapolated from studies which likely underestimate local road mortality. Road mortality surveys can undercount animals who died from WVC by more than one order of magnitude (Slater, 2002). Additionally, areas with low road mortality are not necessarily indicative of areas where roads have less impact on wildlife (Fahrig et al., 1995). These could indicate a strong barrier effect (see following section on The barrier effect) or a previous local extinction (Ascensão et al., 2019; Rytwinski & Fahrig, 2015).

Road surface avoidance behaviour, characterised by wildlife avoiding the conditions present on the road surface, such as the lack of cover and the pavement, is influenced by the physical size of the road. On the other hand, traffic avoidance behaviour, characterised by avoiding oncoming vehicles or periods of high traffic, is influenced by the quantity and frequency of vehicles. Both of these behaviours vary by species and affect their road mortality (Jaeger et al., 2005). Small mammals tend to avoid the road surface, but this does not seem to negatively affect their populations (McGregor et al., 2008; Rytwinski & Fahrig, 2015). Some species can compensate for the road mortality with their high reproductive rates (Rytwinski & Fahrig, 2015). This could explain species where population persistence is not considered threatened by roads, yet have high rates of road mortality. On the other hand, species that are found much less frequently in mortality surveys may be much more impacted by roads (Grilo et al., 2020). Species with large home ranges, typically large mammals, have an increased risk of road mortality because their larger movement patterns make them cross more roads than species with smaller ranges. This behaviour, combined with low reproduction rates, can negatively impact population abundance (Patterson, 2023; Rytwinski & Fahrig, 2015). Because carnivores often have these characteristics, their decreased numbers could reduce predation and counteract the negative effects of roads for species in lower trophic levels, such as deer (Munro et al., 2012). Predation has decreased as a cause of mortality for a range of mammals during the period when the proportion of mortality by WVC rose (Hill et al., 2019).

2.1.2 The verge

While there are many definitions of the verge, this area usually refers to the strip of managed land located on either side of the road which is different from the local habitat. The verge can include many different features like plants, drainage channels, and street lights. These features, and the width of the verge, vary greatly based on location (Forman & Alexander, 1998; Phillips et al., 2020). This area can also slop up to, or down to, the road itself, which happens more frequently for highways than other types of roads and can limit wildlife movement onto/across the road (Grilo et al., 2011). Verges can include many weed and exotic plants species, but can also be beneficial to some native plant species in areas that are highly modified by humans (Lázaro-Lobo & Ervin, 2019). The main, and normally only, way that verges are managed is by mowing, meant to increase visibility and safety for drivers (Forman & Alexander, 1998; Phillips et al., 2020). This activity favours exotic plants, decreases plant species richness, and removes cover for wildlife species, creating a greater gap in cover (Ascensão et al., 2015; Forman & Alexander, 1998). Open habitats, which include mowed and cleared verges, are associated with reduced population abundances compared to forested habitats near roads for mammals (Benítez-López et al., 2010). The rate at which verges are mowed also affects species diversity for animals (Forman & Alexander, 1998). High densities of small mammals have been found in road verges (Bellamy et al., 2000; Grilo et al., 2011). In turn, this presence of prey species in the verge attracts predators to this area, leading to increased road mortality for predator species (Silva et al., 2019). The verge can also be used as a corridor for movement by plants and wildlife (van der Ree et al., 2015).

2.1.3 The road-effect zone

The road-effect zone encompasses all the areas that are impacted by the effects of the road, this includes the road itself, the verge, and all other habitat affected. The size of this zone varies based on local factors (van der Ree et al., 2015). Although road mortality is included in road effects, since it has been previously presented, this section will focus on other road and traffic disturbances. Roads alter hydrological and chemical flows in the road-effect zone. The impervious road surface leads to water runoff and causes sedimentation and erosion, which need to be managed (Coffin, 2007; Forman & Alexander, 1998). Metal and organic pollutants coming from the road and vehicles are carried by this runoff to the local ecosystem and watershed, polluting them (Hwang et al., 2016, 2019). Noise, light, and vibrations are also traffic disturbances, which are controlled by the number of vehicles on the road. Noise is considered the greatest disturbance because it can reach the farthest distance from the road. These disturbances have all been shown to affect wildlife (Forman & Alexander, 1998). Some species do not react to road disturbances, while others will react in a positive or negative manner (Fahrig & Rytwinski, 2009; Jaeger et al., 2005). Traffic disturbances in general reduce habitat quality for species (Fahrig & Rytwinski, 2009). A meta-analysis found that the effects of roads on mammals are frequently reported several kilometers away (Benítez-López et al., 2010). In particular, caribous (*Rangifer tarandus*) show road avoidance behaviour up to 30 km away (Johnson & Russell, 2014). In the United States, it is estimated that up to 20 % of land is located within the road-effect zone (Forman, 2000). These negative effects of roads lead to reduced population densities in the road-effect zone (Benítez-López et al., 2010; Fahrig & Rytwinski, 2009). For animal abundance, negative effects from roads are reported much more frequently than neutral or positive effects (Fahrig & Rytwinski, 2009). The reduction in population abundance near roads for mammals varies based on the size of the species, with larger mammals seeing reductions over much greater distances than small mammals, likely due to larger home ranges (Benítez-López et al., 2010).

2.1.4 The barrier effect

The barrier effect describes how for some species, the road can act as a barrier and prevent animals from crossing. This effect is caused by one or more of the previously presented effects of roads on animals. The barrier can be physical, where animals cannot physically cross one of the road elements, or it can be behavioural. The main reasons for animals to be reluctant to cross the road or the road-effect zone are: lack of cover, visual, auditory, and chemical pollution, traffic, width of the road, combined width of the road and verge, and ground surface material (D’Amico et al., 2016; van der Ree et al., 2015). Road avoidance behaviour increases habitat loss caused by roads (Ascensão et al., 2019; D’Amico et al., 2016). Animals that cannot cross roads are prevented from accessing resources, habitat, and mates located on the other side of the road. Subsequently, genetic diversity and population persistence can be negatively affected (Jaeger et al., 2005; van der Ree et al., 2015). For mammals, the barrier effect is stronger for smaller species and for larger road widths (Chen & Koprowski, 2019).

2.1.5 Landscape fragmentation

The global road network, which includes roads that are paved, unpaved and only seasonally accessible, was recently estimated at 21 million km (Meijer et al., 2018). By 2050, global road length is projected to increase by 60 % above its length in 2010 (Dulac, 2013). Across reported countries, the average road network density is 1.87 km/km^2 of land (International Road Federation, 2021). In Europe, 50 % of land is less than 1.5 km away from transport infrastructure (Torres et al., 2016). Because of the widespread road network in the United States, it was estimated in 2000 that 20 % of the total land area in this country is within the road-effect zone (Forman, 2000). The road network in the United States is now 9.2 % longer than the road length used in this previous estimate, indicating that the road-effect zone may have grown since then (U.S. Department of Transportation Federal Highway Administration, 2023). The increase in roads in the landscape, as well as other human infrastructure, leads to landscape fragmentation. While there are many definitions of landscape fragmentation, it generally refers to the division of the landscape into smaller habitat patches, very often caused by road construction. The new roads are what separates the newly formed patches (Fahrig, 2003). These impacts reduce landscape connectivity, which is the ability for an organism to move freely through the landscape (Taylor et al., 1993). Mammal movement has been strongly reduced in areas with a high human footprint index, which is in part explained by the increased presence of movement barriers, leading to the loss of long-range species in highly modified areas. These changes impact the entire ecosystem (Tucker et al., 2018). In smaller habitat patches, lack of genetic diversity and lower population sizes increase the risk of local extinction

(Jaeger et al., 2005). Moreover, there is concern about the lack of information about the effects landscape fragmentation has on the population persistence of many species (Jaeger, 2015). For example, while research has shown that population persistence reaches a threshold for grey wolves (*Canis lupus*) at road densities above 0.58 km/km^2, meaning this species does not inhabit landscapes with higher road densities, bobcats (*Lynx rufus*) are only known to select home ranges in areas with lower road densities compared to areas with higher road densities (Poessel et al., 2014; Thiel, 1985). The vast majority of species known to be threatened by roads have not been investigated in terms of the effects of roads on their population persistence (Barrientos et al., 2021). Additionally, population persistence may take a long period of time to be affected by landscape fragmentation, and more research on long-term effects at the landscape scale is needed (Barrientos et al., 2021; Jaeger, 2015).

2.2 Mitigation measures

2.2.1 Various types of mitigation measures

Roads are commonly permanent elements of the landscape, and the effects of their implantation on the landscape cannot be fully mitigated (van der Ree et al., 2015). Transport authorities should follow the precaution principle when mitigating the impacts of current or new roads, since the information regarding their impacts is still incomplete, in particular at the landscape scale (Jaeger, 2015). Road mitigation is generally motivated by concerns for human safety caused by WVC and for conservation of wildlife species (van der Grift et al., 2013). There are dozens of different types of road mitigation measures. These measures are typically aimed at reducing road mortality and increasing connectivity. They can vary significantly based on the species targeted, the landscape, the effectiveness desired, and the budget (Rytwinski et al., 2016). The mitigation measures presented in this section are not an exhaustive list but are meant to represent the most common measures.

There are multiple ways to evaluate if mitigation measures are successful. The best endpoint to determine the effectiveness is based on what the measure is directly meant to mitigate. For example, a measure aimed at reducing road mortality should use the amount of road mortality as the endpoint to compare (van der Grift et al., 2013). Many mitigation measures can be combined to try to reduce the impact of roads even more than with a single measure, such as a project with both an array of wildlife passages and wildlife fencing. According to a meta-analysis by Rytwinski et al. (2016), road mitigation measures reduce road mortality by 40 % on average, but this percentage changes drastically for individual mitigation measures or combinations of these. Cheaper mitigation measures are more widespread than expensive mitigation measures, even when research has proven that these cheaper measures are ineffective (Glista et al., 2009; Rytwinski et al., 2016). Road mitigation measures are meant to work by modifying either human behaviour or wildlife behaviour (Grilo et al., 2011; Huijser et al., 2008).

The main ways in which vehicle drivers' behaviour is meant to change is by reducing speed, increasing driver awareness of potential wildlife on the road, and/or increasing the visibility for both drivers and wildlife to see each other and avoid a collision. The most used road mitigation measures to modify human behaviour are static wildlife warning signs. These signs have been shown to not reduce road mortality with large mammals, which they often depict (Huijser et al., 2008; Rytwinski et al., 2016). On the other hand, temporary and seasonal signs seem to help reduce road mortality (Grilo et al., 2011). Signs which are a part of animal detection systems, which detect when an animal is present near the road and warn drivers, effectively reduce road mortality by 57 % for large mammals (Huijser et al., 2008; Rytwinski et al., 2016). Other measures aimed at humans have either mixed results or limited research, these include: increased lighting, vegetation removal, decreased traffic, decreased vehicle speed, among others (Huijser et al., 2008).

Road mitigation measures aimed at modifying animal behaviour include wildlife fencing, wildlife passages, and other less frequently implemented measures. Some measures, such as large wildlife passages, are aimed at a broad range of species, while other measures, such as population control, are generally aimed at one specific species. Population control is mostly aimed at deer to reduce WVC with this species group. Habitat modification, culling, relocation, and anti-fertility treatments are the different options available to lower the deer population near roads (Huijser et al., 2008). Deer whistles and wildlife reflectors, meant to scare away wildlife from oncoming vehicles, are ineffective. Olfactory repellants also seem to be mostly ineffective. These three previous measures can suffer from wildlife habituation over time and become less effective (Grilo et al., 2011; Huijser et al., 2008; Rytwinski et al., 2016). These mitigation measures do not reduce WVC with other species and can have a negative impact on the surrounding ecosystem (Huijser et al., 2008). Wildlife fencing is an effective way to reduce road mortality, with a 54 % average reduction (Rytwinski et al., 2016). Wildlife fencing can be applied to a broad range of species and prevent them from accessing the road. There are many ways to customize fencing for target species: high fencing, overhangs, fencing that extends underground, small mesh size, and metal sheathing are some of the features that can be added or changed (Grilo et al., 2011). One risk of wildlife fencing is that animals become trapped inside of the fence. To mitigate this, one-way doors need to be installed in the fence, typically in the form of ramps with jumps or one-way gates (Huijser et al., 2008). Fences can also increase the barrier effect (Jaeger & Fahrig, 2004). Animals attempting to cross the road may follow the fence until the end and cross there, creating a WVC hotspot at both ends and negating the reduction of mortality in the fenced area. This phenomenon is known as the fence-end effect and decreases the effectiveness of wildlife fencing (Plante et al., 2019; Rytwinski et al., 2016; Wilansky & Jaeger, 2024). Wildlife crosswalks and animal detection systems can be used to mitigate the fence-end effect (Grilo et al., 2011; Huijser et al., 2008).

2.2.2 Wildlife passages and other structures

Crossing structures can be divided into three categories: wildlife passages, multi-use structures, and existing structures (Warnock-Juteau et al., 2022). Wildlife passages are usually overpasses and underpasses built for the explicit purpose of facilitating safe animal movement across the road (Denneboom et al., 2021). Their size varies greatly based on the species targeted. The widths of structures for small mammals and herpetofauna can be as small as 0.3 m, while wildlife overpasses can be dozens of meters wide for large mammals (Clevenger & Huijser, 2011; Clevenger & Waltho, 2005; Glista et al., 2009). The substrate of the structures should match the local soil substrate to maximise use by wildlife (Clevenger & Huijser, 2011; Glista et al., 2009). Ideally, wildlife passages should be designed to accommodate the widest range of species possible, with more consideration given to species with a greater conservation concern (Clevenger & Huijser, 2011). Wildlife passage characteristics should be adapted to the target species to optimize mitigation (Soanes et al., 2024). Wildlife passages are among the most expensive wildlife mitigation measures to build, with the construction cost of wildlife overpasses in the millions of dollars per structure (Denneboom et al., 2021; Raibaldi, 2020).

Multi-use structures are structures built with the intention of being used by both humans and wildlife (Warnock-Juteau et al., 2022). For example: a pedestrian vegetated bridge over a highway serving both wildlife and human crossing needs. These types of structures can be less expensive to build than two separate structures meant to individually satisfy the needs of humans and wildlife (van der Ree & van der Grift, 2015). However, use of the structures by humans may limit the use by certain species (Asari et al., 2020; Warnock-Juteau et al., 2022). In particular, multi-use structures are rarely used by large carnivores compared to dedicated wildlife passages (Denneboom et al., 2021).

Existing structures, unlike the two previous groups that prioritised wildlife, are structures built into the road to facilitate water or human movement (Warnock-Juteau et al., 2022). These structures, which include water culverts, bridges, road underpasses, and several others, punctuate the road by creating tunnels through which animals can cross without needing to step onto the road surface or avoid moving vehicles. These structures are an already common feature of roads and could provide a much more frequent habitat linkage for wildlife than singular wildlife passage projects (Clevenger et al., 2001; Seiler & Olsson, 2010; van der Ree et al., 2011). Existing structures also vary greatly in shape, size, and material, and have been used by many different wildlife species. Every size of mammal has been reported crossing these structures, even moose (*Alces alces*) (Bhardwaj et al., 2020; Brunen et al., 2020; Clevenger et al., 2001; Grilo et al., 2008; Warnock-Juteau et al., 2022). Existing structures located near streams have a higher species richness, likely because riparian habitat acts as a natural corridor. This places bridges and water culverts in convenient locations for wildlife use (Glista et al., 2009; Jensen et al., 2022). Existing structures meant for water can be modified by adding dry ledges to offer a dry path for animals to use them to cross (Villalva et al., 2013). Other structures may also present such dry paths, although these paths were not intended for wildlife use when the structures were built (Niemi et al., 2014). The cost of modifying or retrofitting existing structures to improve wildlife use is low, especially when compared to the high cost of building new wildlife passages (Mata et al., 2008; Smith et al., 2015). These existing structures can be included in regional plans to mitigate the impacts of roads on wildlife and improve connectivity (Paemelaere et al., 2023).

Scientific research on wildlife passages has mainly focused on which species use them, how often they use them, and what characteristics influence their use (van der Grift et al., 2013). While these are important metrics, the effectiveness of wildlife passages should be evaluated based on animal movement. Depending on the aim of the wildlife passage project, there are different ways to evaluate this movement (Soanes et al., 2024). Research about the mitigation effect from wildlife passages of road impacts on wildlife populations is more limited. Population and gene-flow research is especially small (Corlatti et al., 2009; van der Grift et al., 2013). Wildlife passages reduce the barrier effect from roads for many species (Soanes et al., 2024). Studies on the influence of wildlife passages on road mortality are more common (Rytwinski et al., 2016). Wildlife passages alone do not seem to reduce mortality. Only with the addition of wildlife fencing, this combination of mitigation measures reduces road mortality in large mammals by 83 %. Studies of fencing alone show a greater reduction in mortality of all species than fencing and wildlife passages combined, but this result is probably due to longer average fence lengths for projects that do not have wildlife passages (Rytwinski et al., 2016). The effects of dry paths in existing structures on the reduction of road mortality are mixed, but the modification of structures to add dry ledges does improve wildlife movement (Niemi et al., 2014; Soanes et al., 2024; Villalva et al., 2013). While crossing structures may or may not fully restore wildlife movements to the level they were prior to the barrier effect caused by roads, the evidence of their use by many species is encouraging and in line with achieving a limited-net-loss target scenario for mitigation (Soanes et al., 2024; van der Grift et al., 2013).

2.2.3 Wildlife passage characteristics

A wide variety of wildlife passages have been constructed across the world, and each structure or group of structures are accompanied by their own unique set of characteristics. Increasing knowledge about how these characteristics influence the use of wildlife passages by wildlife would improve cost-effective design (Denneboom et al., 2021). In a systematic review, Denneboom et al. (2021) found 28 commonly reported independent characteristics of wildlife passages listed in previous research. While the use of wildlife passages by different species groups is affected by different characteristics, and different species groups may have opposing preferences of the same characteristic, a few general trends across species help promote the use of wildlife passages, these are: large open structures, natural materials, and fencing (Denneboom et al., 2021). Wildlife passages use is also influenced by seasonality, time of day, and human use (Serronha et al., 2013; Warnock-Juteau et al., 2022; Ważna et al., 2020). Water presence significantly reduces the use of wildlife passages by many species (Brunen et al., 2020; Serronha et al., 2013; Ważna et al., 2020). Carnivores are particularly reticent to use structures with human use. Although when human use is limited, structural characteristics influence use more than landscape variables (Clevenger & Waltho, 2005; Denneboom et al., 2021). In general, researchers recommend a variety of wildlife passages to provide suitable structures for all species in the ecosystem (Clevenger & Waltho, 2005; Denneboom et al., 2021; Helldin, 2022).

2.2.4 Known existing structure use near the study area

Previous research in the Eastern Townships, a region east of the Laurentides in Quebec, and in Vermont, a state southeast of the Laurentides in the United States, has evaluated the use of existing structures in these areas. These studies have been focused on water culverts, bridges, and vehicle underpasses (Brunen et al., 2020; Marangelo, 2019; Warnock-Juteau et al., 2022). In each study, approximately a dozen mammal species was recorded going through existing structures, and the species recorded were very similar. This included local mammals of all sizes, both predator and prey species. Domestic cats (*Felis catus*) and dogs (*Canis familiaris*) were also recorded. For the two Eastern Townships studies, the species with the most detections was raccoon (*Procyon lotor*), followed by white-tailed deer (*Odocoileus virginianus*). In contrast in Vermont, Marangelo et al. (2019) did not record the number of raccoon detections, but this species was simply highlighted as being very abundant, and deer was the most common focal species recorded. All studies found that the rates at which animals crossed through the structures varied significantly between sites (Brunen et al., 2020; Marangelo, 2019; Warnock-Juteau et al., 2022).

2.3 Road ecology in the Laurentides

2.3.1 A portrait of the Laurentides

The administrative region of the Laurentides in the province of Quebec, Canada, a large portion of which is visible in Figure 3.3.1, has a land area of 20,548 km^2 and is located north of the islands of Laval and Montreal (Institut de la statistique du Québec, 2023). In the most recent census of 2021, the population of the Laurentides was 636,083. This represents a 7.9 % increase from the previous 2016 census (Statistics Canada, 2022). While the overall population density of the Laurentides is 30.9 people per km^2, most of this population is concentrated in the southern part of this region, which is included in the *Communauté métropolitaine de Montréal* (CMM; Montreal Metropolitan Community) (Laberge, 2019; Statistics Canada, 2022). Urban sprawl is a major concern in the Laurentides. The southern municipalities part of the CMM have had the Metropolitan Land Use and Development Plan for more than a decade to limit this sprawl. Despite this, municipalities bordering the CMM continue to have a high rate of single-family home construction and an increased number of residents using personal vehicles to travel to the CMM for work (Corriveau, 2020; Observatoire Grand Montréal, 2020).

The major industries of the Laurentides are agriculture, mainly in the southern section, as well as forestry and tourism (Lemieux, 2018). Large portions of the Laurentides previously used for agriculture in the 19th century were abandoned and naturally reforested in the 20th century. The territory reforesting coincided with urban development and development on lake shores for leisure, increasing landscape fragmentation (Roy et al., 2009). The Laurentides region also saw a large logging industry in the 19th and 20th centuries, but the intensive logging led to a depletion of timber resources, a decrease in many tree species, and the decline of the industry (Roy et al., 2009). The area of the Laurentides studied in this research is part of the sugar maple (*Acer saccharum*) – yellow birch (*Betula alleghaniensis*) bioclimatic domain, which is characterised by these two species and the American beech (*Fagus grandifolia*) (Ministère des Forêts, de la Faune et des Parcs du Québec, 2021). At the Saint-Hippolyte weather station, the highest average monthly temperature is 18.9 °C in July and the lowest average monthly temperature is -12.5 °C in January. This area receives 900.5 mm of rain and 296.7 mm of snow on average per year (MELCCFP, 2023b). The Laurentides area under study is part of the Canadian shield, which is characterised by hills and lakes (Barrett, 2021).

The species distribution record held by the Quebec government indicates that 56 mammal species are present within the Laurentides (MELCCFP, 2023a). Hunting and pelt sale data also confirm the presence of many of these mammals in the region (Gouvernement du Québec, 2022a, 2022b). According to the government of Quebec, excluding bats, none of the mammal species in this area are vulnerable or threatened, but three species of vole and the southern flying squirrel (*Glaucomys volans*) are considered susceptible to be designated vulnerable or threatened (Gouvernement du Québec, 2023). The eastern wolf (*Canis sp. cf. lycaon*) is a species of special concern for the government of Canada, but this species is not recognised by the Quebec government and falls under grey wolf (Environment and Climate Change Canada, 2021).

The Laurentides have two IUCN category II national parks: Parc national du Mont-Tremblant and Parc national d'Oka (Gouvernement du Québec, 2018). Mont-Tremblant welcomes 3 million visitors annually, making the Laurentides the third most important touristic area in Quebec (Colpron, 2020). In 2024, only 8.89 % of the territory of the Laurentides region was designated as a protected area, which is far from the goal of 30 % by 2030 (Environment and Climate Change Canada, 2023; MELCCFP, 2024). The three municipalités régionales de comté (MRC; regional county municipality) covered by this research from south to north are MRC de la Rivière-du-Nord, MRC des Pays-d'en-Haut, and MRC des Laurentides. Respectively, 79.4 %, 94.1 %, and 91.6 % of their area is covered by forests, other vegetation, and wetlands. All have seen increases in natural and anthropogenic fragmentation elements (waterbodies, human infrastructure, agriculture, etc.) since 1992, with MRC de la Rivière-du-Nord seeing the largest increase of fragmentation and the greatest reduction in combined vegetated habitats of 4.4 % (Cole, Kross, et al., 2023). The three MRCs have road densities ranging from 0.94 km/km^2 to 2.5 km/km^2, which includes all paved road classes and local gravel roads. While the southernmost MRC has the highest road density, the road density increased significantly more in the other two MRCs between 1992 and 2018 (Cole, Kross, et al., 2023).

The Laurentides are included in the Adirondack-to-Laurentians wildlife linkage, providing a north-south corridor for wildlife species (Cole, Kross, et al., 2023). In the Laurentides, a spatial analysis found that habitat patches for moose and black bear (*Ursus americanus*) were greatly reduced between 2000 and 2015 (Cole, Koen, et al., 2023). Through Resolution 40-3, governments in northeastern North America have agreed that ecological connectivity needs to be included in conservation and land planning (St-Pierre et al., 2019). This could mitigate the impacts of climate change by maintaining or restoring the resiliency of ecosystems (St-Pierre et al., 2019). Previous mapping of the Laurentides by Éco-corridors laurentiens (ÉCL) has established priority ecological corridors, shown in Figure 3.3.1, linking the two national parks present in this region (Després-Einspenner et al., 2020). Ecological corridors are linear landscape areas that connect important natural habitats that have been previously fragmented, i.e., they aim to improve or restore connectivity (Lemieux, 2018). The mapping done by ÉCL was based on six focal species and two focal species groups. The goal of each umbrella species selected was to represent the needs of many others. Grey wolf, American marten (*Martes americana*), northern short-tailed shrew (*Blarina brevicauda*), white-tailed deer, and moose were the focal mammal species chosen. All species have a moderate or great sensitivity to the barrier effect. White-tailed deer and moose are also concerns for road safety due to WVC. ÉCL and the Ministère des Transports et de la Mobilité durable du Québec (MTMD) prioritize these two species for this reason and consider them in the planning of potential wildlife passages. The analysis done by ÉCL also considered the specific needs of species in relation to roads and vegetation (Després-Einspenner et al., 2020). ÉCL's primary mission is to help conserve natural areas and preserve ecological corridors in the Laurentides region. Mapping these corridors helps them achieve these goals (Éco-corridors laurentiens, 2022). At a larger scale, ÉCL is a member of the Quebec Ecological Corridors Initiative, which aims to improve connectivity in the whole province of Quebec (Initiative québécoise Corridors écologiques, 2023).

2.3.2 Two major Laurentides roads

Two particularly important landscape features of this region are Autoroute 15 (A-15), also known as the Autoroute des Laurentides in its northern part, and Route 117 (R-117), a national road (MTMD, 2023d, 2023a). These are the two main roads that bisect the Laurentides into a northeastern and a southwestern region (Boucher, 2013). Prior to these, the train track Le P'tit train du Nord was built around the turn of the 20^{th} century to connect the Laurentides (Goudreau, 2022). This railway was built next to La Rivière du Nord, a river that guided colonisation in the area (Roy et al., 2009). R-117, at the time known as Route 11, was graveled in 1926 (Aubry, 2023). R-117 follows roughly the path of the railroad, criss-crossing it at some points. This road starts south of the Laurentides, in Montreal, and ends northwest of the Laurentides, crossing the entire span of this region. In the 1950s, heavy traffic and tourism prompted the Quebec government to build its first highway, which became A-15 (Cordeau, 2022). This highway runs parallel to and criss-crosses R-117. A-15 was completed in 1974 and ends north of Sainte-Agathe-des-Monts, where it exits onto R-117 (Cordeau, 2022). A-15 represents approximately 75 km of highway in the Laurentides (Google Maps, n.d.). Both roads were constructed without any wildlife mitigation measures. The construction of these roads lead to the closure of Le P'tit train du Nord in 1981, which was then turned into a cycling path in 1996 (Cordeau, 2022; Goudreau, 2022). The construction of these roads has also contributed to landscape fragmentation in the Laurentides (Roy et al., 2009). Tourists coming from Montreal must now take A-15 and R-117 to reach Mont-Tremblant. Between St-Jérôme and Mont-Tremblant, most of R-117 and A-15 have two lanes per direction, vegetated medians, and speed limits of 90 km/h and 100 km/h, respectively. Anthropogenic development in the region has mainly occurred next to these two major roads, as evidenced by the map in Cole, Kross, et al. (2023) and the global human footprint index, where development traces their outline (Wildlife Conservation Society and Center for International Earth Science Information Network, 2023).

Animal movement from Parc national du Mont-Tremblant to Parc national d'Oka requires the crossing of either R-117, or both A-15 and R-117 (Boucher, 2013). Maintaining ecological connectivity between these to parks benefits both biodiversity and humanity and lessens anthropogenic pressure on this region (Després-Einspenner et al., 2020). GPS data from wolves in Parc National du Mont-Tremblant, whose genomes were primarily of the eastern wolf type, show that they only cross R-117 north of La Conception, where the AADT is greatly reduced compared to the road prior (Malcolm et al., 2020; MTMD, 2023d; Rogic et al., 2014). In 2022, A-15 had an AADT of 118,000 vehicles/day south of St-Jérôme, which decreases heading north. At the junction of R-117 and A-15 north of Sainte-Agathe-des-Monts, the AADT becomes 22,500 vehicles/day, and stays consistent on the R-117 up to right before the city of Mont-Tremblant (MTMD, 2023d). The AADT since 2013 has increased on both roads; the section of road leading to the city of Mont-Tremblant saw a 31 % increase in 10 years (MTMD, 2023d). This road section also had 96 % higher daily traffic in summer months compared to winter months in 2022. Both roads experience this higher daily traffic in warmer months (MTMD, 2023d). A-15 and R-117 intersect with priority ecological corridors identified by ÉCL (Després-Einspenner et al., 2020; Lemieux, 2018).

WVC data are reported by the MTMD in the Laurentides, but many WVC lack species information and collisions with animals smaller than 25 kg are not reported (Éducaloi, n.d.;

Raibaldi, 2020). Although one category of species of recorded WVC includes bear, moose, or caribou, caribou is not found within the Laurentides and would not be part of WVC data (MELCCFP, 2023a; Raibaldi, 2020). Some road mortality hotspots found by Raibaldi (2020) on A-15 are located within ecological corridors. Additionally, Raibaldi (2020) found an average of 50.7 WVC per year with large mammals on A-15 in the Laurentides. Most of these collisions are with white-tailed deer, and approximately 3 % are with black bear or moose (Raibaldi, 2020).

The cost of these reported WVC was on average $595,417 annually between 2013 and 2017, and this cost should be considered a minimum (Raibaldi, 2020). In the entire Laurentides area, there were 5,173 reported collisions with white-tailed deer and 146 collisions with black bear or moose between 2010 and 2017 (Lemieux, 2018). WVC in the Laurentides are mainly located on the major roads, with the highest concentrations on A-15 and R-117 (Lemieux, 2018). Lemieux (2018) recommends the installation of wildlife passages on A-15 and R-117 in Prévost and on R-117 in Saint-Faustin-Lac-Carré (now Mont-Blanc), which are both located in ecological corridors mapped by ÉCL. This recommendation was issued without knowing the state of existing structures in the area. Subsequently, Raibaldi (2020) recommended the evaluation of these structures in terms of their physical characteristics and locations. Raibaldi (2020) also recommended a partnership between a university and an organisation, such as ÉCL, to perform a permeability analysis of existing crossing structures.

Road mitigation measures are almost inexistant in the Laurentides for A-15 and R-117. A few ineffective static road signs are present. In Ivry-sur-le-lac, the old train underpass under R-117 now used for the cycling path that has been lightly naturalised with the intention of increasing wildlife use (Conservation de la nature Canada, n.d.; Jean Boulé, personal communication, March 2022). Recently, the MTMD announced that two large wildlife underpasses and multiple additional smaller ones would be built during the future widening of R-

117 between Labelle and Rivière-Rouge, farther north than La Conception and outside of the study area (MTMD, 2023b).

3 Manuscrit : Efficacité limitée des ponts et ponceaux non aménagés pour la connectivité des mammifères dans les Laurentides

3.1 Résumé

Dans la région des Laurentides, le réseau écologique reliant les parcs nationaux d'Oka et du Mont-Tremblant est interrompu par l'autoroute 15 (A-15) et la route 117 (R-117). Néanmoins, entre Saint-Jérôme et Mont-Tremblant, aucun passage faunique n'a été construit le long de ces axes routiers. En revanche, de nombreuses structures existent dans l'emprise routière qui pourraient être utilisées par la faune pour traverser les routes en sécurité. Pour examiner cette idée, nous avons évalué l'utilisation par les mammifères de 2 ponts et de 8 grands ponceaux sous l'A-15 et la R-117 de juin 2022 à décembre 2023. Des caméras ont été installées de part et d'autre des sites pour déterminer quelles espèces traversaient ces structures. Nous avons observé plus de 4 000 détections de mammifères d'au moins 20 espèces de toutes tailles et nous avons confirmé qu'au minimum 19,2 % des animaux détectés ont traversé avec succès, provenant de 11 espèces. L'utilisation des structures existantes a varié considérablement par espèce et par structure. Certaines structures ont été traversées plus d'une centaine de fois, tandis qu'une autre ne l'a jamais été. Le manque de substrat sec pour traverser semble être un facteur très limitant. De plus, plusieurs espèces parapluies présentes dans les Laurentides et répertoriées dans les collisions véhicules-faune n'ont pas été observées. Pour améliorer la connectivité écologique, les structures existantes faiblement utilisées devraient être aménagées, notamment pour permettre à la faune de traverser au sec. Nous recommandons également l'ajout de clôtures pour guider la faune vers les structures et la construction de passages fauniques pour les espèces n'utilisant pas ou peu les structures existantes.

Mots-clés : caméras, écologie routière, mesure d'atténuation, passage faunique

3.2 Titre et résumé anglais

Title: Limited effectiveness of unmitigated bridges and culverts for mammal connectivity in the Laurentides

In the Laurentides (Québec, Canada), Autoroute 15 (A-15) and Route 117 (R-117) transect the network of eco-corridors between the Parc national d'Oka and the Parc national du Mont-Tremblant. Although there are no purpose-built wildlife passages along these two roads, there are several existing structures between Saint-Jérôme and Mont-Tremblant that wildlife could use to cross them safely. To investigate their potential use by mammals, cameras were installed on both sides of 2 bridges and 8 large water culverts. Between June 2022 and December 2023, over 4,000 mammal detections were made, involving at least 20 species of all sizes. At least 19.2% of the detections involved a successful crossing, completed by 11 species. The use of the structures varied significantly by species and by structure. One structure was never successfully used, while mammals successfully crossed others over 100 times. The lack of a dry path through a given structure seems to be an important limiting factor. In addition, several umbrella species present in the Laurentides and reported in wildlife-vehicle collisions were not recorded at all. To improve ecological connectivity, existing structures with low usage should be modified, notably by incorporating a dry pathway through them. Fences should be added to help guide and funnel wildlife to the structures. Finally, suitable wildlife passages should be constructed for those species not or rarely using the existing structures.

Keywords: cameras, crossing structures, mitigation measures, road ecology

3.3 Mise en contexte et objectifs

La région des Laurentides au Québec est reconnue pour ses grands massifs forestiers, ainsi que la richesse et l'intégrité de ses milieux naturels. Toutefois, la croissance de l'étalement urbain et du morcellement de ce territoire nuit à la connectivité entre les habitats naturels et à la résilience écologique de leurs écosystèmes (Cole, Kross, et al., 2023). En 2020, Éco-corridors laurentiens (ÉCL), un organisme ayant pour vision de connecter les milieux naturels des Laurentides, a réalisé une analyse de connectivité reliant le parc national d'Oka au parc national du Mont-Tremblant en utilisant plusieurs espèces parapluies (dont l'habitat doit être sauvegardé pour que soient conservées d'autres espèces, parmi lesquelles certaines sont rares et menacées) et en tenant compte de leurs types d'habitats, de leur capacité de dispersion et de leur sensibilité aux barrières (Després-Einspenner et al., 2020). Les 5 espèces de la classe des mammifères sélectionnées étaient : le cerf de Virginie (*Odocoileus virginianus*), la grande musaraigne (*Blarina brevicauda*), le loup (*Canis lupus*), la martre d'Amérique (*Martes americana*) et l'orignal (*Alces alces*). L'autoroute 15 (A-15) et la route 117 (R-117) ont été identifiées par ÉCL comme 2 barrières majeures à la connectivité des Laurentides. Plusieurs des corridors écologiques modélisés, d'une largeur minimale de 1 km, ou de 500 m en milieu agricole, sont scindés par ces 2 routes (Després-Einspenner et al., 2020), comme il est illustré à la Figure 3.3.1. L'urbanisation des Laurentides est principalement concentrée autour de ces routes, amplifiant leur effet barrière sur la faune (Cole, Kross, et al., 2023). De plus, l'A-15 et la R-117 sont le théâtre d'un nombre important de collisions avec les grands mammifères, présentant un enjeu sociétal considérable en matière d'économie et de sécurité humaine (Raibaldi, 2020). Bien que les routes puissent avoir des répercussions négatives sur tous les groupes d'espèces, les mammifères à grands domaines vitaux et à faibles taux de reproduction sont affectés disproportionnellement (Patterson, 2023; Rytwinski & Fahrig, 2012). Le loup figure parmi les espèces à grand domaine vital présentes dans les Laurentides, notamment le loup de l'Est (*Canis sp. cf. lycaon*), qui se trouve au parc national du Mont-Tremblant et est désigné menacé au Canada en 2024 (Comité sur la situation des espèces en péril au Canada, 2015; Rogic et al., 2014).

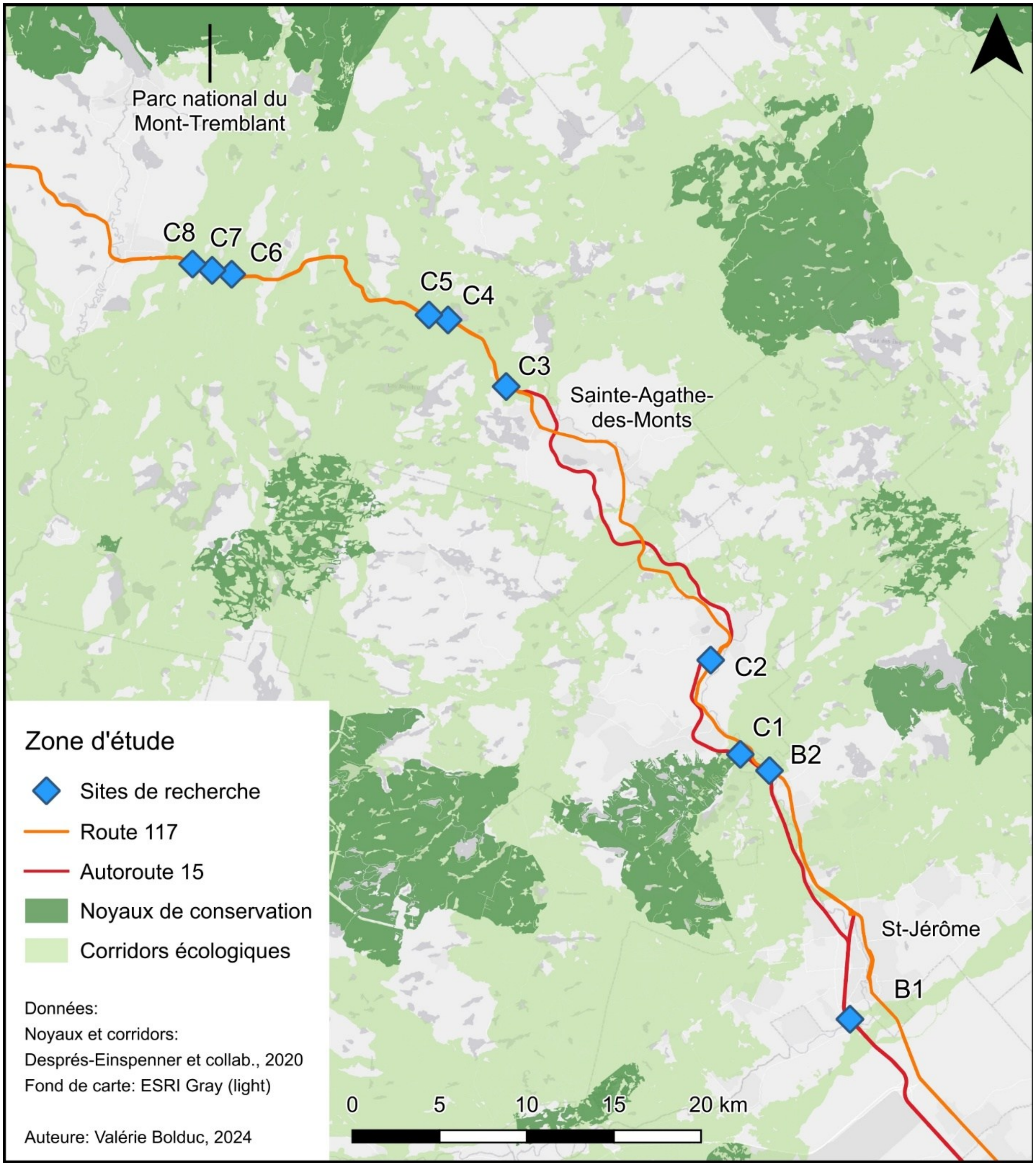

Figure 3.3.1 Carte des Laurentides : sites de recherche, noyaux de conservation, corridors écologiques et routes.

L’installation de passages fauniques est une mesure efficace pour restaurer en partie la connectivité fragmentée par les routes (Soanes et al., 2024). Dans les Laurentides, l’A-15 et la R-117 ne disposent actuellement d’aucun passage faunique construit spécifiquement pour la faune, à l’exception d’une ancienne structure ferroviaire aménagée en sentier cyclable et permettant le passage de la faune à Ivry-sur-le-Lac. Ce passage a été aménagé par Conservation de la nature Canada, et la faune y est suivie par caméras depuis 2019 par ÉCL (Conservation de la nature Canada, n.d.). La construction de quelques passages fauniques est prévue par le MTMD (2023c) lors de l’élargissement de la R-117 au nord de Mont-Tremblant. Pourtant, dans l’emprise routière actuelle, des structures existantes comme les ponts et ponceaux sont déjà présentes et peuvent, dans certains cas, rendre les routes plus perméables à la faune. L’utilisation de ces structures dépend de certains éléments de conception tels que la taille, le niveau d’eau et le matériau utilisé (Brunen et al., 2020; Craveiro et al., 2019; Seiler & Olsson, 2010).

L’étude de l’utilisation des structures existantes par les mammifères permet d’atteindre 2 objectifs : d’une part, comprendre quelles structures sont les plus fréquemment empruntées afin d’intégrer leurs caractéristiques dans l’aménagement des ponts et ponceaux pour en augmenter l’usage ; d’autre part, concevoir des passages fauniques adaptés aux espèces qui traversent peu ou pas les structures actuelles (Denneboom et al., 2021). Cela pourrait alors permettre de cibler les mesures d’atténuation afin de soutenir à la fois les espèces utilisatrices et non-utilisatrices, augmentant ainsi la connectivité pour l’ensemble des espèces. De plus, combiner l’utilisation faunique aux autres fonctions des structures existantes permet d’augmenter la connectivité écologique à plus faible coût que de construire de nouvelles structures entièrement dédiées à la faune. En outre, l’installation systématique de ponts et ponceaux au sein de l’infrastructure routière pourrait créer un large réseau de structures accommodant la faune, qui peuvent alors être combinées avec d’autres mesures d’atténuation comme les clôtures fauniques pour minimiser l'impact des routes (Rytwinski et al., 2016; Seiler & Olsson, 2010; Spanowicz et al., 2020). Ainsi, les objectifs de recherche sont :

1. Caractériser et évaluer l'utilisation des structures existantes de grande taille par les mammifères sous l'A-15 et la R-117 dans les Laurentides ;
2. Identifier des différences dans l'utilisation des structures existantes de grande taille en fonction de leurs caractéristiques physiques ;
3. Déterminer quelles espèces de mammifères présentes dans les Laurentides n'utilisent pas les structures existantes de grande taille.

3.4 Méthodologie

Notre zone d'étude s'étendait sur 75 km, entre les villes de Saint-Jérôme et de Mont-Tremblant, sur l'A-15 et la R-117 (Figure 3.3.1). En collaboration avec le MTMD, nous avons sélectionné 11 sites de recherche représentatifs des grandes structures existantes dans les Laurentides, montrés à la Figure 3.4.1. Ces sites, tous entourés par des habitats forestiers et des bandes riveraines (visibles à la Figure 3.4.1), étaient connectés à de plus grands milieux naturels par ceux-ci, offrant ainsi un potentiel accru d'utilisation par les mammifères, conformément aux données de la littérature (Denneboom et al., 2021). Il n'a pas été possible de choisir des sites entièrement naturels en raison de la fragmentation du paysage au pourtour des routes étudiées. Tous les sites étaient ainsi situés à moins de 50 m d'éléments anthropiques : résidence privée, zone commerciale, route secondaire, clôture de ferme, ligne électrique aérienne, ou sentier de vélo ou de motoneige. Le pourcentage de milieux naturels entourant les sites variait entre 26,7 et 89,2 %. Celui-ci a été calculé à l'aide d'un rayon de 500 m autour de chaque site avec les données d'utilisation du territoire, d'une résolution de 10 m, en suivant la

Figure 3.4.1 Photos des sites de recherche (B = pont [bridge], C = ponceau [culvert]).

formule : 1 – (proportion de milieu anthropique + proportion de milieu agricole) (MELCCFP, 2023c). La densité routière, quant à elle, variait entre 2,7 et 7,4 km/km^2, calculée sur 1 km^2 entourant chaque site (Statistique Canada, 2024). De ces structures, 2 étaient des ponts chevauchant la rivière du Nord, dont 1 de ces ponts était divisé en 2 sites de recherche, et 8 étaient des grands ponceaux rectangulaires en béton. La hauteur des ouvertures des structures variait de 1,7 à 4,0 m, la largeur de 3,0 à 68,7 m et la longueur de 12,8 à 58,3 m. Nous avons mesuré le niveau d'eau sur 2 journées en septembre 2023. À chaque visite durant les 17 mois de l'étude, le niveau d'eau était de ± 5 cm de ce niveau, excepté durant les inondations d'avril 2023. Nous avons suivi la faune sur seulement une berge de chaque site en raison du nombre limité de caméras, sauf au pont B2. Pour cette structure, aussi connue sous le nom du pont du Boys Farm à Prévost, nous avons suivi les 2 berges en raison de la différence marquée entre elles, ainsi que de sa reconstruction prévue prochainement. Par conséquent, la berge nord était le site B2 nord et la berge sud était le site B2 sud. Des informations supplémentaires sur ces sites sont présentées au Tableau 3.4.1.

De juin 2022 à décembre 2023, sur chacun des sites, nous avons installé 4 caméras infrarouges à détection de mouvement Reconyx Hyperfire HC600, selon la configuration présentée à la Figure 3.4.2, à l'exception du site B1. Au site B1, nous avons installé seulement 2 caméras aux positions 2 et 3, émettant l'hypothèse selon laquelle cette structure serait moins utilisée par la faune à cause du développement urbain important à proximité. De plus, le nombre réduit de caméras nous a permis de diminuer le risque de vandalisme sur ce site. Les caméras ont été placées à une hauteur de 1,2 m, avec un angle légèrement vers le bas par rapport à l'horizontale, ou un angle plus prononcé sur un sol pentu (Figure 3.4.2). Nous avons configuré les caméras en mode détection de mouvement seulement, avec une haute sensibilité, 5 photos par mouvement, et un intervalle RapidFire entre les photos. L'entretien des caméras a été effectué chaque 6 à 12 semaines durant les 17 mois de la période d'étude. Nous avons

Tableau 3.4.1 Caractéristiques géographiques, physiques et environnementales de chaque site. Débit journalier moyen annuel (DJMA) provenant du MTMD (2023d). Pour les sites avec 2 structures : les données de hauteur, largeur et longueur sont une moyenne des valeurs des 2 structures.

	Unité	B1	B2	C1	C2	C3	C4	C5	C6	C7	C8
Latitude	° Nord	45,7533	45,8780	45,8852	45,9325	46,0653	46,0970	46,0984	46,1110	46,1124	46,1148
Longitude	° Ouest	-74,0150	-74,0891	-74,1113	-74,1385	-74,3068	-74,3532	-74,3659	-74,5154	-74,5307	-74,5457
Kilomètre		40	55,5	57	65,5	90	95,5	96,5	110	111,5	112,5
Nom de route		A-15	R-117	A-15	R-117	R-117	R-117	R-117	R-117	R-117	R-117
DJMA (2022)	Véhicules/ jour	118 000	10 800	52 000	7 900	22 500	22 500	22 500	24 000	24 000	24 000
Type de structure		Pont	Pont	Ponceau	Ponceau	Ponceau	Ponceau	Ponceau	Ponceau	Ponceau	Ponceau
Nombre de structures		2	1	1	1	2	2	2	2	2	2
Taille de la médiane	m	25				13	30	6	22	24	27
Hauteur	m	2,3	4,0	1,8	2,3	2,0	1,7	2,1	1,8	3,2	2,4
Largeur	m	60,6	68,7	3,7	4,6	14,4	14,6	7,8	3,0	5,9	6,1
Longueur par structure	m	19,2	13,9	58,3	33,4	16,0	12,8	12,8	31,9	32,9	33,8
Profondeur d'eau minimale à franchir	cm	0	0	0	40	0	0	5	25	10	10
Corridor écologique		Non	Oui	Oui	Non	Oui	Oui	Oui	Oui	Oui	Oui
Milieu naturel	%	26,7	41,3	58,1	59,8	71,4	89,2	82,4	42,8	71	60,3
Densité routière	km/km^2	4,7	7,4	7,0	7,3	4,8	2,7	2,7	4,3	3,7	2,8

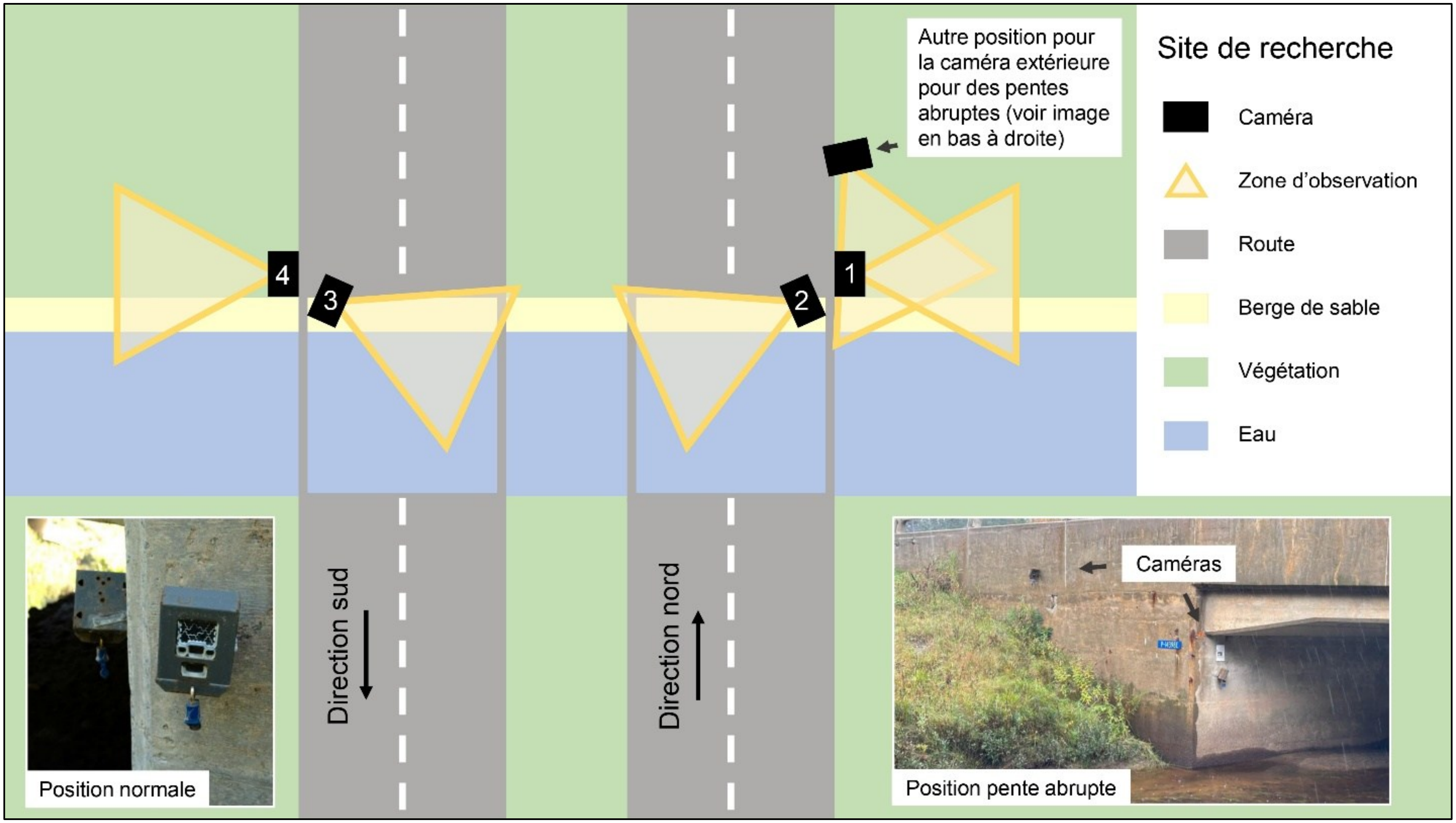

Figure 3.4.2 Schéma de la disposition des caméras sur un site, en vue aérienne.

utilisé l'algorithme d'intelligence artificielle MegaDetector version MDv5a avec un seuil de confiance de 0,10-1,00 pour retirer les photos « vides », qui ne contenaient ni animaux ni humains, et le logiciel Timelapse pour effectuer la saisie de données des photos manuellement (Beery et al., 2019; Greenberg, 2023).

Lors de l'analyse des photos, lorsque 2 individus de la même espèce, sans différence physique évidente, étaient observés dans un intervalle de moins de 20 min, ils étaient considérés comme une seule et même détection, sauf si plusieurs individus étaient observés sur la même photo. Dans ce cas, chaque individu sur la même photo était comptabilisé comme une détection. Si celle-ci était captée par au moins une des caméras de chaque côté du site (caméra 1 ou 2 et caméra 3 ou 4) durant la période de 20 min, l'animal était réputé avoir fait une « traversée complète ». Si l'animal n'entrait pas dans la structure, ou entrait puis faisait demi-tour, la mention « non traversé » lui était attribuée. Si la détection ne remplissait pas les critères pour une « traversée complète » ou « non traversé », mais était observée par les caméras 2 ou 3, elle était attribuée à la catégorie « observé à l'intérieur ». Si aucun de ces cas ne s'appliquait, elle était attribuée à la catégorie « observé à l'extérieur ».

En raison de la difficulté à identifier certaines espèces, 5 groupes regroupant plusieurs espèces ont été créés parmi l'ensemble des animaux détectés (espèces et groupes d'espèces). Le groupe « écureuil » comprenait les écureuils gris (*Sciurus carolinensis*) et roux (*Tamiasciurus hudsonicus*). Le groupe « belette ou hermine » (*Mustela sp.*) et le groupe « campagnol ou souris » (espèce indéterminée) rassemblaient toutes les détections de ces animaux, et chacun de ces 3 groupes était traité comme 1 seule espèce lors des analyses. Le groupe « Mustelidae » regroupait tous les membres de cette famille dont l'espèce n'avait pu être identifiée, tout comme le groupe « espèce inconnue ». Ces 2 derniers groupes n'étaient pas pris en compte dans le nombre total d'espèces, car les espèces correspondant à ces individus étaient probablement déjà identifiées sur le site. Enfin, toutes les détections d'humains et celles des autres espèces animales présentes sur les photos ont également été comptabilisées. Par la suite, les données de détection ont été compilées et analysées par espèce et par site. Ces données ont alors été comparées aux caractéristiques des structures mesurées sur le terrain ou fournies par le MTMD. Afin d'identifier les espèces présentes dans la région, mais qui n'ont pas utilisé les structures existantes au courant de la période d'étude, les données sur la faune ont été comparées aux informations d'occurrences du Système mondial d'information sur la biodiversité (GBIF.org, 2024), aux aires de répartition des mammifères terrestres du ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs du Québec (MELCCFP, 2023a), aux collisions véhicules-faune répertoriées par le MTMD dans Raibaldi (2020) et au projet Stop Carcasses ! (Laurentides) (iNaturalist, 2024).

3.5 Résultats et discussion

3.5.1 Utilisation des structures par les mammifères

Les caméras ont pris 531 000 photos au total (incluant les photos « vides »). Parmi ces photos, nous avons observé 4 169 détections de mammifères de 20 espèces ou de groupes d'espèces différents (Figure 3.5.1). De ces détections, nous avons pu confirmer qu'au moins 800 animaux ont fait une traversée complète (19,2 % des détections) et 194 n'ont pas fait de traversée (4,7 % des détections). Pour les 3 175 détections restantes, 51,7 % ont été observées à l'intérieur de la structure. Les résultats pour chaque espèce ou chaque groupe d'espèces par site sont disponibles à l'Annexe 7.1 et sont comparés à la Figure 3.5.2. L'espèce la plus observée a été le raton laveur (*Procyon lotor*), avec 1 860 détections, représentant 44,6 % de toutes les détections et 61,5 % de toutes les traversées complètes. Le cerf de Virginie, l'écureuil et la marmotte (*Marmota monax*) ont tous eu de 427 à 517 détections (Figure 3.5.2). Ces 3

Figure 3.5.1 Photos des animaux sur les sites. De haut en bas, colonne de gauche : vison d'Amérique, belette ou hermine, écureuil, ratons laveurs. Colonne de droite : renard roux, cerf de Virginie, ratons laveurs, castor.

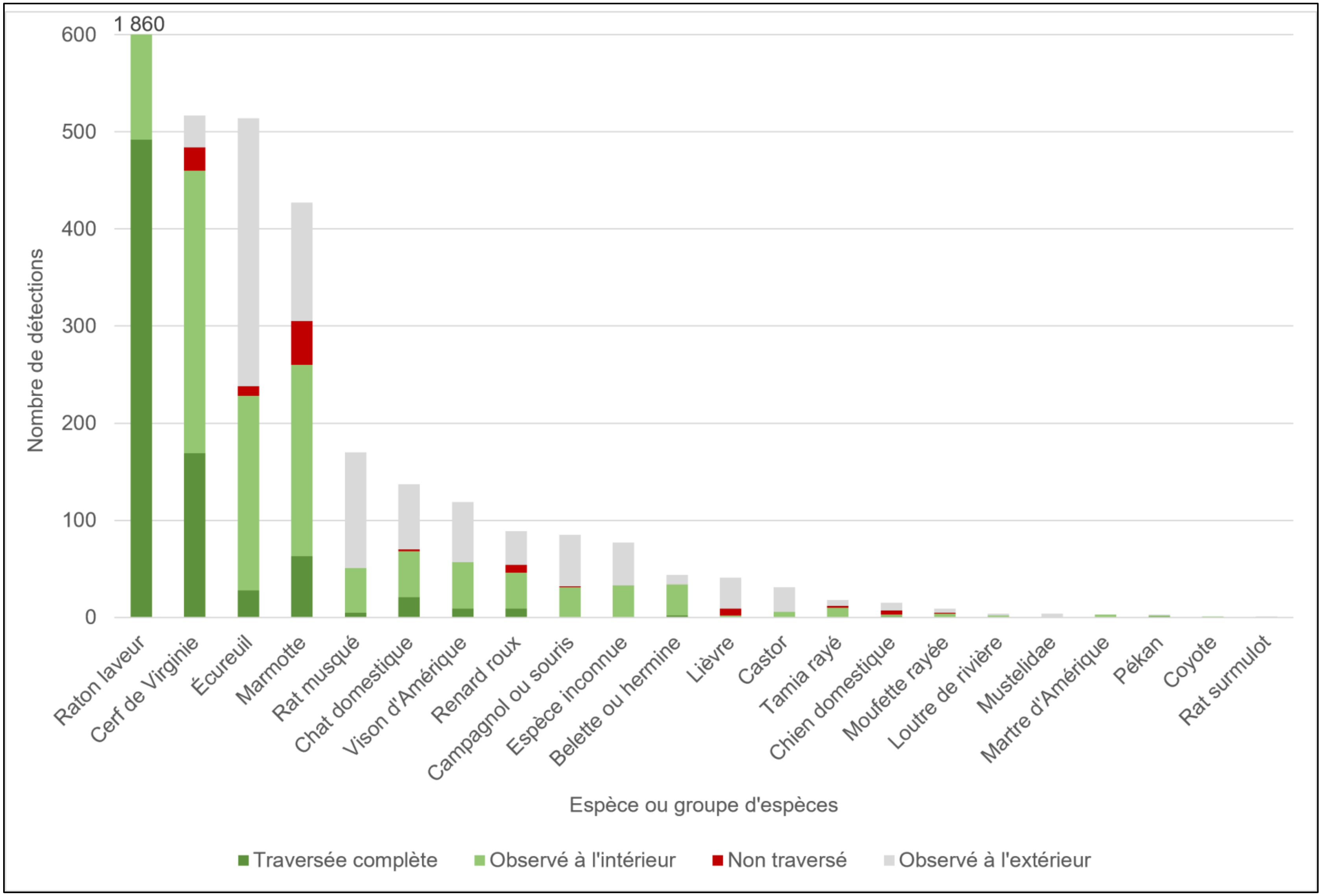

Figure 3.5.2 Nombre de détections par espèce ou groupe d'espèces, tous sites confondus, selon le type de détection.

dernières espèces ont été observées sur 10 des 11 sites, tandis que le raton laveur a été la seule espèce observée sur tous les sites. Les 16 autres espèces ont été observées à 170 reprises ou moins, et 6 espèces ont été observées à moins de 10 reprises. Onze espèces ont fait au moins une traversée complète et toutes les espèces ont été observées à l'intérieur des structures, à l'exception du rat surmulot (*Rattus norvegicus*) avec un seul individu observé. En moyenne, chaque espèce a été observée sur 5,85 sites (53 % des sites).

Deux études et un rapport sur l'utilisation par les mammifères des ponceaux dans les Cantons-de-l'Est et au Vermont avec des méthodes, des ponceaux et un nombre de structures similaires aux nôtres ont rapporté des observations semblables à celles des Laurentides, particulièrement pour les espèces les plus fréquemment observées. Ainsi, le raton laveur et le cerf de Virginie arrivent aux premiers rangs dans toutes ces régions quant au nombre de détections (Brunen et al., 2020; Marangelo, 2019; Warnock-Juteau et al., 2022).

Au niveau du comportement, 5 espèces ont été observées à la nage : castor (*Castor canadensis*), pékan (*Pekania pennanti*), rat musqué (*Ondatra zibethicus*), raton laveur et vison d'Amérique (*Neovison vison*). Trois espèces supplémentaires ont été observées ayant au moins une patte ou un sabot dans l'eau : cerf de Virginie, chien domestique (*Canis familiaris*) et marmotte. De toutes les détections, 11,7 % ont été observées dans l'eau.

Une des limitations des observations par espèce réside dans la difficulté à détecter les petits mammifères, une contrainte qui pourrait être atténuée en ajustant la hauteur des caméras à celle du corps de ces animaux (Jumeau et al., 2017). Ainsi, les espèces de plus petite taille, telles que les groupes belette ou hermine, campagnol ou souris, écureuil et tamia rayé (*Tamias striatus*), ont eu des taux de traversée complète plus faibles que les espèces de grande taille. Pour les observations de type « à la nage », il était plus difficile de déterminer si les individus avaient traversé ou non les structures. Plusieurs d'entre eux n'avaient probablement pas été détectés à nouveau de l'autre côté puisqu'ils nageaient à l'extérieur de la zone d'observation des caméras, ou étaient sous l'eau dans cette zone.

Pour les corridors écologiques, les sites B1 et C2 étaient les 2 seuls sites à l'extérieur des corridors et leurs nombres d'espèces et de détections étaient comparables aux sites situés à l'intérieur des corridors. Seules 2 des espèces parapluies de mammifères utilisés pour l'analyse de connectivité ont été observées au cours de l'étude : le cerf de Virginie, détecté à la fois à l'intérieur et à l'extérieur des corridors identifiés pour cette espèce, et la martre d'Amérique, uniquement observée à l'extérieur des corridors qui lui sont attribués (Després-Einspenner et al., 2020). Les sites C4 et C5, bien qu'ayant les pourcentages les plus élevés de milieux naturels et les densités routières les plus faibles, n'ont pas montré de différence claire en ce qui concerne le nombre d'espèces ou de détections par rapport aux autres sites. Le site C4 a d'ailleurs enregistré le deuxième plus faible nombre de détections, qui pourrait être attribué à la faible détection de ratons laveurs à ce site. D'autres études ont examiné l'influence du milieu environnant sur l'utilisation des structures existantes par les mammifères en employant une zone tampon. À l'aide d'une zone tampon de 300 m, Ascensão et Mira (2007) ont montré que, selon l'espèce, le pourcentage de milieux ouverts pouvait soit en augmenter ou en diminuer l'utilisation. De manière similaire, à l'aide d'une zone tampon de 500 m, Serronha et al. (2013) ont observé que les renards roux (*Vulpes vulpes*) utilisaient moins les structures dans les zones d'agriculture extensive.

Des humains ont visité chaque site de recherche de 1,4 à 4,8 fois par mois et l'équipe de recherche représentait la moitié de ces visites. En ordre décroissant, certaines autres activités humaines aux sites étaient : la pêche, les inspections du MTMD, le canot et le kayak, le trappage et le graffiti. De plus, 759 oiseaux ont été observés au total, soit de 5 à 170 oiseaux par site.

3.5.2 Différences dans les caractéristiques physiques

3.5.2.1 Ponceaux

La Figure 3.5.3 présente les résultats pour l'ensemble des mammifères, répartis par site. Elle met en évidence des différences notables dans le nombre de traversées complètes selon les sites étudiés. Le site C6 était le seul site où aucune traversée complète n'a été observée. De plus, sur ce site, la seule espèce animale capturée par les caméras faisant face à l'intérieur de la structure a été le grand héron (*Ardea herodias*). Le site C2, quant à lui, a enregistré le deuxième plus petit nombre de traversées complètes et de mammifères observés à l'intérieur. Ces 2 sites partageaient une caractéristique commune : un niveau d'eau minimal élevé à franchir, avec 40 cm pour C2 et 25 cm pour C6. Aux sites C5, C7 et C8, presque toutes les traversées complètes ont été effectuées par des ratons laveurs, à l'exception d'une traversée sur les 2 premiers sites. Ces sites présentaient tous un niveau d'eau minimal de 5 cm, ce qui pourrait également limiter l'accessibilité pour certaines espèces.

Plusieurs ponceaux disposaient d'une berge sèche d'un côté, mais celle-ci ne se prolongeait pas jusqu'à l'autre extrémité. Des détections d'espèces réticentes à aller dans l'eau ont été observées à l'intérieur de ces ponceaux et celles-ci ont potentiellement fait demi-tour lorsque le chemin sec prenait fin. Cela pourrait expliquer pourquoi certaines des espèces, comme l'écureuil présenté à la Figure 3.5.1, ont été observées à l'intérieur des structures, sans que l'on puisse conclure à une traversée complète. Bien que les ratons laveurs aient traversé les 3 ponceaux présentant des niveaux d'eau entre 5 et 10 cm, aucun d'entre eux n'a franchi le site C2, où le niveau d'eau atteignait au moins 40 cm. À cet endroit, les ratons laveurs approchaient le ponceau par la zone riveraine et gravissaient la pente menant à la route par-dessus, puis redescendaient de l'autre côté. Pour les sites avec ponceau, C1 et C3 disposaient

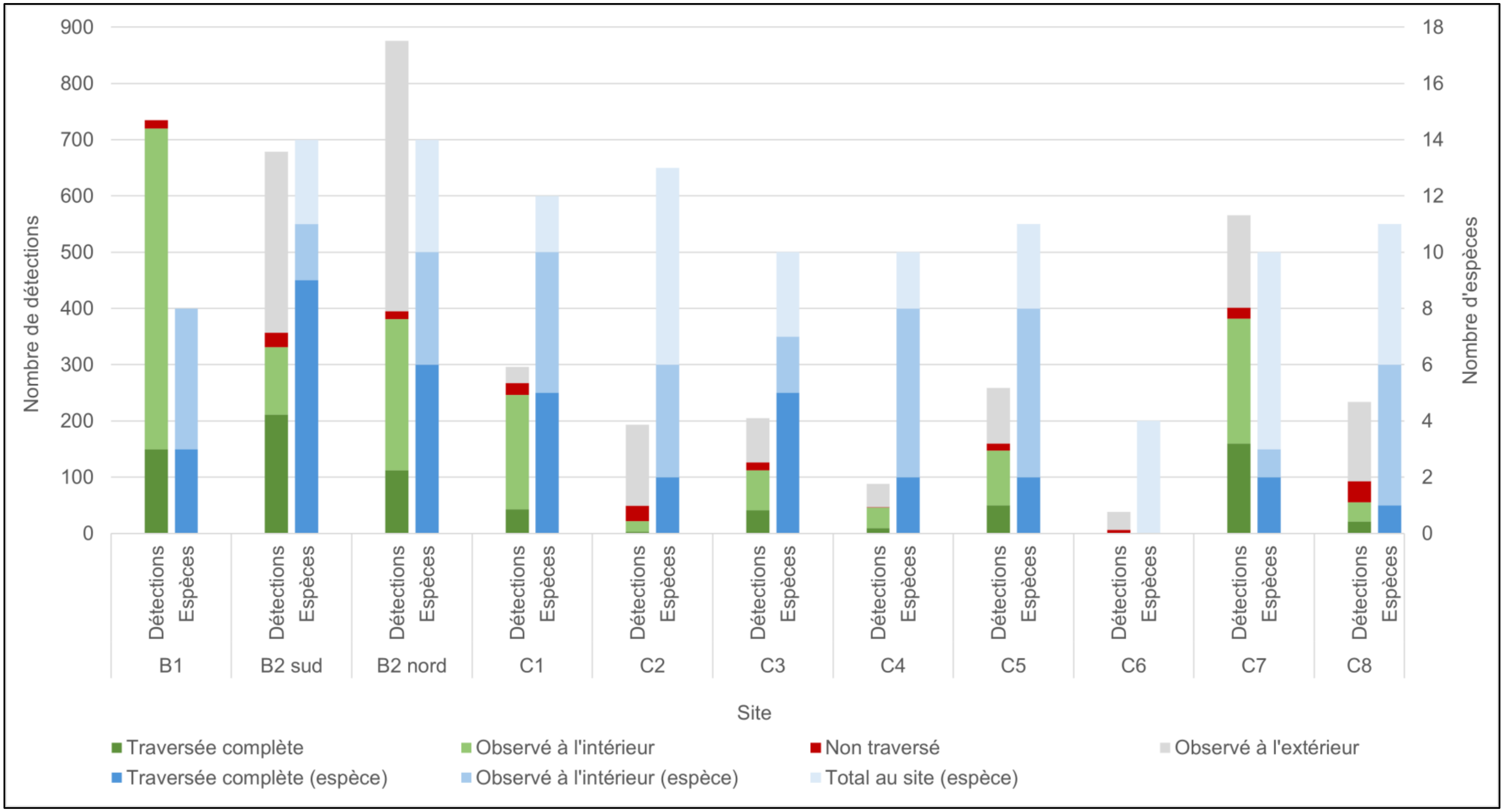

Figure 3.5.3 Nombre de détections et nombre d'espèces par site, selon le type de détection.

des plus larges berges sèches continues et ont également enregistré le plus d'espèces ayant fait au moins une traversée complète, avec 5 espèces par site. Plusieurs études démontrent qu'un bas niveau d'eau, ainsi que la présence de chemins secs, encouragent les traversées complètes dans les ponceaux (Brunen et al., 2020; Craveiro et al., 2019; Serronha et al., 2013), ce que nos résultats corroborent également.

Une différence majeure entre le site C2, avec 3 traversées complètes, et le site C6, avec aucune traversée complète, était la taille de l'ouverture (hauteur × largeur du ponceau), qui était beaucoup plus petite pour C6. De plus, le site C1, qui était à l'origine un ancien passage pour bétail, présentait une ouverture de taille similaire à celle de C6, mais contenait très peu d'eau à l'intérieur du ponceau. Ainsi, la taille de l'ouverture pourrait avoir un impact sur le nombre de traversées complètes dans les structures avec un plus haut niveau d'eau.

3.5.2.2 Ponts

À chacun des 3 sites avec un pont, on a enregistré au moins 112 traversées complètes et 679 détections, un nombre nettement supérieur aux 7 sites avec ponceaux. Seul le ponceau C7 a comptabilisé plus de 50 traversées complètes et plus de 300 détections. Le site B1, avec seulement 2 caméras orientées vers l'intérieur, a montré approximativement 2 fois plus d'observations de la faune que B2 sud et B2 nord, une fois les détections observées à l'extérieur du pont B2 exclues. Par conséquent, l'hypothèse selon laquelle le site B1 serait moins utilisé par la faune est rejetée sur la base du nombre absolu de détections. Cependant, ce nombre peut être expliqué par la quantité accrue de détections de cerfs de Virginie à ce site, représentant 73,1 % des détections de cette espèce dans notre étude. Les espèces observées au site B1 étaient majoritairement synanthropiques : cerf de Virginie, coyote (*Canis latrans*), écureuil, lièvre (*Lepus sp.*), marmotte, moufette rayée (*Mephitis mephitis*), raton laveur et renard roux, ce qui différait des autres sites qui avaient tous un plus haut pourcentage de milieux naturels (voir annexe 7.1). Ce résultat concorde avec Ascensão et Mira (2007) qui avaient déterminé que les sites près de zones urbaines étaient plus utilisés par les espèces synanthropiques. Pour B1, le nombre d'espèces ayant effectué au moins une traversée complète et le nombre d'espèces observées sur le site étaient comparables à ceux des sites avec ponceaux, bien que ces valeurs pourraient être plus élevées si le nombre de caméras avait été équivalent aux autres sites. Pour les sites B2 sud et B2 nord, le nombre d'espèces observées était supérieur à celui de tous les autres sites, même si la densité routière y était la plus élevée.

Les 3 sites avec pont comportaient des différences physiques importantes avec celles des ponceaux. La taille de l'ouverture des ponts était de 5 à 10 fois supérieure à celle des ponceaux, et la largeur de la berge sèche était également beaucoup plus grande aux sites B1 et B2 nord par rapport aux ponceaux dotés de berges. Ces facteurs pourraient expliquer l'utilisation accrue des ponts comparativement aux ponceaux, une tendance confirmée par d'autres études (Craveiro et al., 2019; Denneboom et al., 2021).

3.5.3 Espèces peu ou jamais observées

La zone abrite plusieurs espèces de mammifères qui ont été peu, voire pas observées au cours de cette étude. Parmi les grands mammifères, nous avons recensé 517 cerfs de Virginie et 1 coyote, mais aucun loup, lynx du Canada (*Lynx canadensis*), lynx roux (*Lynx rufus*), orignal (*Alces alces*) ou ours noir (*Ursus americanus*) (GBIF.org, 2024; MELCCFP, 2023a; Raibaldi, 2020). Cependant, nous savons que plusieurs de ces espèces tentent de traverser les routes de la zone d'étude, puisqu'environ 13 collisions impliquant des ours noirs ou des orignaux sont signalées chaque année sur les 50 km de l'A-15 (Raibaldi, 2020). Concernant les mésomammifères, aucun porc-épic d'Amérique (*Erethizon dorsatum*) n'a été observé, bien que plusieurs carcasses aient été signalées le long des routes par le biais d'une plateforme de science citoyenne (iNaturalist, 2024). Moins de 5 détections ont été enregistrées pour la loutre de rivière (*Lontra canadensis*), la martre d'Amérique et le pékan, ce dernier n'ayant été observé qu'au site B2 sud. Enfin, pour les petits mammifères, plusieurs groupes taxonomiques, tels que musaraignes, polatouches et taupes, n'ont pas été détectés (GBIF.org, 2024; MELCCFP, 2023a).

Contrairement à nos résultats, toutes les études sur les ponceaux non aménagés menées dans les Cantons-de-l'Est et au Vermont ont rapporté des observations de lynx roux, d'ours noirs et de porcs-épics d'Amérique, et 2 d'entre elles ont également signalé la présence d'orignaux (Brunen et al., 2020; Marangelo, 2019; Warnock-Juteau et al., 2022). Les différences observées entre ces études et la nôtre pourraient s'expliquer par les variations des milieux environnants, ce qui pourrait également influencer les résultats obtenus pour chaque site. Marangelo (2019) notait d'ailleurs que plusieurs de ces sites à faible utilisation avaient un plus fort développement humain à proximité. Tandis que plusieurs sites étudiés par Brunen et al. (2020) et Warnock-Juteau et al. (2022) étaient situés en bordure du parc national du Mont-Orford, offrant ainsi un noyau de conservation majeur à proximité.

3.6 Recommandations

Nous recommandons plusieurs modifications physiques aux structures existantes et à celles destinées à être reconstruites. Des berges sèches, des pieds secs ou des tablettes devraient être ajoutés aux structures qui n'en sont actuellement pas pourvues (voir Jaeger et al. (2019) et Trocmé et Righetti (2012) pour des exemples et des propositions de normes). L'agrandissement des ponceaux est également nécessaire pour faciliter leur utilisation par les espèces réticentes à traverser en raison de l'espace restreint. Des clôtures devraient être installées pour guider la faune vers les structures et empêcher les mammifères d'emprunter la route, réduisant ainsi le risque de mortalité. Nous avons constaté ce problème de mortalité lors de nos visites sur le terrain, notamment avec la découverte de 2 carcasses de moufettes rayées sur la route au-dessus du site C3, où aucune traversée complète n'a été observée pour cette espèce. Ces clôtures doivent être suffisamment longues pour éviter l'effet de « bout de clôture » (Huijser et al., 2016; Jaeger et al., 2019; Lafrance & Alain, 2019; Plante et al., 2019), selon l'approche détaillée par Wilansky et Jaeger (2024). Concernant le pont du Boys Farm, nous recommandons de conserver les berges sèches après la reconstruction afin de faciliter la traversée de la faune.

Les futures mesures d'atténuation visant à restaurer la connectivité dans les Laurentides devraient cibler les espèces peu ou jamais observées lors de notre étude, notamment en construisant des passages fauniques spécifiques. Les caractéristiques physiques de ces passages devraient être basées sur les éléments de conception connus pour favoriser leur utilisation par les espèces qui n'utilisent pas ou peu les ponts et grands ponceaux (Denneboom et al., 2021). Des recherches supplémentaires sont également nécessaires pour comprendre pourquoi certaines espèces signalées dans les ponceaux des Cantons-de-l'Est et du Vermont n'ont pas été rapportées dans ceux des Laurentides.

3.7 Conclusion

Cette étude a permis de noter que de multiples espèces de mammifères, comme le raton laveur, le cerf de Virginie, l'écureuil et la marmotte, traversent régulièrement les ponts et ponceaux sous l'A-15 et la R-117 dans les Laurentides. Nous avons également constaté que 11 espèces avaient effectué au moins une traversée complète, tandis que 19 espèces ont été observées à l'intérieur de ces structures et pourraient les traverser lorsque leurs caractéristiques le permettent.

Plusieurs caractéristiques semblent en effet influencer l'utilisation des structures par les mammifères. Celles présentant un niveau d'eau élevé ont été les moins, voire jamais traversées, alors que les ponceaux disposant de larges berges sèches ont permis à un plus grand nombre d'espèces d'effectuer des traversées complètes. Les sites comprenant un pont, tous dotés d'une berge sèche et d'une large ouverture, ont accueilli significativement plus de mammifères que les sites avec ponceau, à l'exception d'un ponceau où les ratons laveurs prédominaient. Ainsi, la capacité des ponts et ponceaux à faciliter la traversée des routes par les mammifères semble dépendre du type de structure et des espèces concernées. Dans la majorité des cas, les grands ponceaux sont inadéquats pour permettre à plusieurs espèces de mammifères de les traverser.

4 Manuscript: Water Depth Deters Mammal Species from Crossing Unmitigated Bridges and Large Water Culverts Under Roads

4.1 Abstract

Various mammals cross through water culverts and bridges underneath roads, which could be optimized for landscape connectivity. Using trail cameras, we monitored mammals for 17 months in and around eight large water culverts and two bridges in the Laurentides region. We hypothesised that water levels, species-specific predisposition for moving through water, termed water-tolerance, and local species presence would influence the use of these structures. We categorised and evaluated species based on their detection within water in our dataset. Small and medium-sized mammals near our sites were identified using track boxes deployed for 20 weeks over two years, concurrent with camera monitoring. We assessed which water-related factors, local fauna, or other predictors influenced culvert and bridge use, and if these varied by mammal group or species using both model averaging on candidate generalised linear mixed models (GLMMs) and GLMMs with interaction effects. Only water-tolerant mammals made full crossings through structures without continuous dry paths, but high water depths had a strong deterrent effect on both water-tolerant and water-intolerant species. Track-box results were similar across sites, indicating that sites with fewer camera detections were not less frequented because of an absence of local fauna. These findings support the inclusion of dry ledges or shelves, especially in water culverts, to facilitate use by a greater range of species and increase connectivity. To guide animals to the structures that already possess these features, we recommend adding wildlife fencing.

Keywords: Road ecology, road mortality, mitigation measures, wildlife passages, trail cameras

4.2 Introduction

4.2.1 Effects of roads on mammals and mitigation measures

The habitat loss and decline in landscape connectivity caused by forest fragmentation and urban sprawl pose significant threats to biodiversity. Globally, urban development nearly doubled between 1990 and 2014, and by 2015, 70% of forest areas were located within one kilometer of the forest edge (Behnisch et al., 2022; Haddad et al., 2015). These lead to a decline in mammal movement, as mammals in areas with a high global human footprint index show lower vagility than their counterparts in more natural areas (Tucker et al., 2018). The road network is an inherent part of anthropogenic landscapes and it is known to impact all vertebrate animal classes (Fahrig & Rytwinski, 2009; Rytwinski & Fahrig, 2015). In addition to the habitat loss within the road-effect zone, animals may be affected by road mortality, road avoidance behavior, and the barrier effect, leading to possible population isolation and local extinction (Benítez-López et al., 2010; Jaeger et al., 2005; Rytwinski & Fahrig, 2015). The mammal species at greatest risk of population decline are those with larger home ranges, often encompassing many roads, and lower reproductive rates, which increases the difficulty of replacing individuals lost due to road mortality (Patterson, 2023; Rytwinski & Fahrig, 2015). The fragmentation of landscapes also reduces the genetic diversity of mammals, particularly for those with a higher body mass (Lino et al., 2019).

An array of mitigation measures have been developed to attempt to reduce road impacts on wildlife (Grilo et al., 2011; Huijser et al., 2008). One metric often used, particularly important for transportation agencies, is the reduction of road mortality. Thus, lowering the high costs associated with large-mammal wildlife-vehicle collisions can present a return on investment for these measures (Huijser et al., 2009; Rytwinski et al., 2016). Both wildlife fencing and the combination of wildlife fencing and wildlife passages have been the most effective at reducing road mortality (Rytwinski et al., 2016). However, these results do not consider changes in landscape connectivity. Wildlife passages, including both underpasses and overpasses, are designed and constructed using a wide range of sizes and characteristics with the aim of improving movement for target species (Smith et al., 2015). Studies have repeatedly shown that mammals and herpetofauna use these structures, with specific taxa responding to differing, and sometimes opposite, structural and environmental variables (Denneboom et al., 2021). These structures are often successful at allowing species to cross roads more safely (e.g., Soanes et al., 2024), however, more research is needed to better understand the impact of these structures on connectivity and the barrier effect across species and structure types.

4.2.2 Bridges and water culverts

Previous research has identified the potential of bridges and water culverts to act as an alternative to wildlife passages. Encouragingly, mammals of various species have previously been shown to cross through some of these structures which present many benefits for mitigation planning (Seiler & Olsson, 2010). They are strategically located within riparian zones, which are acting as natural corridors funneling wildlife towards them (Grilo et al., 2008; Jensen et al., 2022). This infrastructure is also either already built within the roadway or is budgeted for in the construction of new roads, as cost is a barrier for implementation of mitigation measures (Glista et al., 2009; Seiler & Olsson, 2010). Furthermore, the costs associated with structural modifications to existing infrastructure, such as adding dry ledges or shelves, are much lower than those for building new dedicated wildlife passages (Mata et al., 2008; Smith et al., 2015). Although the number of existing unmitigated bridges and water culverts far exceeds the number of wildlife passages, they have been much less studied than their counterparts (Seiler & Olsson, 2010; van der Ree et al., 2011). Nonetheless, the structural (e.g., size, material, shape) and environmental (e.g., vegetation, fencing, human activity) variables measured can be very similar to those of wildlife passages (Denneboom et al., 2021; Seiler & Olsson, 2010). However, the largest difference between these structure types is the presence or absence of water, sometimes covering the entire surface area within the structure opening (Serronha et al., 2013). A few studies about mammals have considered predictors related to water, such as depth and coverage, and evaluated their relationships with the use of culverts and bridges. A lower water coverage and the presence of a dry path within the structure seem to increase mammal use, whilst higher water depth decreases it, but these results vary by species (Brunen et al., 2020; Craveiro et al., 2019; Grilo et al., 2008; Jensen et al., 2022; Marangelo, 2019; Serronha et al., 2013; Sparks & Gates, 2012). For transportation agencies, expanding this knowledge is essential to make informed decisions about modifying bridges and water culverts to improve mammal movement, and to incorporate these designs into environmental impact assessments (Jaeger, 2015; Paemelaere et al., 2023; van der Ree et al., 2011). Advancing knowledge in these areas could be particularly advantageous for Quebec, where the Ministère des Transports et de la Mobilité durable du Québec (MTMD) has officially begun considering ecological connectivity within their infrastructure network in 2025 (MTMD, 2025a).

4.2.3 Geographical context

The administrative region of the Laurentides is located north of the city of Montreal in the province of Quebec, Canada. Most of the region, and all the study area, is located within the Canadian shield, which is characterised by its hills and lakes, and within the sugar maple (*Acer saccharum*) – yellow birch (*Betula alleghaniensis*) bioclimatic domain (Ministère des Forêts, de la Faune et des Parcs du Québec, 2021). The region receives 0.9 m of rain and 3.0 m of snow annually, while average monthly temperatures range from -12.5°C in January to 18.9°C in July (MELCCFP, 2023b). The southern Laurentides are part of the traditional and unceded territory of the Kanyen'kehà:ka (Mohawk), Omàmìwininìwag (Algonquin), and Anishinabewaki, the Indigenous people of the region (Abler, 2006; Indigenous Services Canada, 2024, Native Land Digital, n.d.). Forestry and agriculture dominated the landscape of this region in the 19th and early 20th centuries. The decline of these industries in the 20th century allowed many no-longer exploited areas to regenerate naturally through reforestation. Concurrently, tourism increased greatly, leading to significant development on lakeshores for cottages, which amplified fragmentation (Lemieux, 2018; Roy et al., 2009). The population of the region rose during all of these periods, and increased by 7.9% during the most recent census period between 2016 to 2021 (Statistics Canada, 2022). To meet the growing leisure demand, the Quebec government built Autoroute 15 (A-15) from Montreal to Sainte-Agathe-des-Monts, the first highway in the province, opening it in sections from 1958 to 1974 without an environmental impact assessment. Running parallel to it, Route 117 (R-117) and *Le P'tit train du Nord* had previously been the main road and railroad connecting the largest towns and cities in the region to one another, and R-117 has continued this role north of A-15 (Cordeau, 2022). The train track has since been removed due to lack of demand and transformed into a cycling path (Goudreau, 2022). Within the study area, these roads had annual average daily traffic volumes between 7,600 to 120,000 vehicles/day in 2023, and these values have increased by up to 30% since 2013 (MTMD, 2025b). The Global Human Footprint Index and Figure 1 in Cole, Kross, et al. (2023) show that human development has been concentrated along A-15 and R-117 in the Laurentides (Wildlife Conservation Society and Center for International Earth Science Information Network, 2023). Between 1992 and 2018, the proportion of natural and anthropogenic fragmentation elements increased by between 5.6% and 21.7% in the three regional county municipalities within which the research sites are located (Cole, Kross, et al., 2023).

To counteract these pressures, the Quebec government has pledged to protect 30% of the province's land by 2030; however, as of 2024, less than 9% of the Laurentides region was protected (MELCCFP, 2022; SNAP Québec, 2024). The largest contributor at 1,510 km^2 has remained the *Parc national du Mont-Tremblant*, one of two IUCN Category II parks in the area, along with the smaller *Parc national d'Oka* (MELCCFP, 2024; Sépaq, 2025). In 2020, Éco-corridors laurentiens (ÉCL), a local non-governmental conservation organisation with a mission to reconnect natural areas in the Laurentides, performed a connectivity analysis of the region. Because of the location of the parks on either side of A-15 and R-117, all priority ecological corridors mapped to link them were completely bisected (Després-Einspenner et al., 2020). No mitigation measures have been implemented on these road sections, except for the naturalisation of an underpass for the cycling path of *Le P'tit train du Nord* (Nature Conservancy of Canada, n.d.). Typically, in Quebec, mitigation measures such as wildlife underpasses and fencing are implemented only when roads are newly built or widened. On a section of R-117 north of the research area being widened in 2025, multiple wildlife passages are scheduled to be installed. These mitigation measures are prioritized despite research showing that wildlife-vehicle collisions represented a considerable cost to society in other areas in the many road mortality hotspots on this road axis, such as along A-15 (Lemieux, 2018; MTMD, 2023c; Raibaldi, 2020).

4.3 Research questions

In our previous study, published in French in the regional journal *Le Naturaliste Canadien* (Bolduc et al., 2025), we identified mammal species that used large water culverts and bridges to cross roads in the Laurentides (Appendices 7.2.5, 7.2.6, and 7.2.8). We summarized the previous article, along with translated figures and tables as supplementary material. Species use varied significantly by site (Appendix 7.2.7) and we discussed how high water depth in the culverts likely deterred mammals, given their lack of use of sites with this characteristic. We also determined that many species present in the Laurentides and detected at culverts in other regions were not detected at our sites, especially large mammals. In this study, we analyse the data regarding the relationships between water-related predictors, water-tolerant species compared to other mammal species, small and medium species in the surrounding habitat, and mammal use of structures. This new research aims to answer the following questions:

1. How do water-tolerant mammal species differ from other species in their use of bridges and large water culverts to cross roads?
2. What predictors, in particular related to water, influence the use of bridges and large water culverts by mammals, and how do these differ among species or species groups?
3. Which small and medium-sized mammal species are present near bridges and large water culverts, and how are the species observed in the culverts and bridges related to those observed in their vicinity?

4.4 Methods

4.4.1 Site selection

Our research area was located along a span of 75 km along A-15 and R-117 in the Laurentides, see Appendix 7.2.1. This limit was chosen because St-Jérôme, the southeasternmost city, is the lower extent of the Canadian shield, after which the St. Lawrence Lowlands start. The northwesternmost city, Mont-Tremblant, was chosen based on its high tourism (Quessy, 2021) and the important decrease in annual average daily traffic west of it (MTMD, 2025b). Based on expert advice from the MTMD, ÉCL, and the Comité regional pour la protection des falaises, we chose 11 sites: two bridges, with one divided into two sites (B1, B2 south and B2 north), with widths of 60.6 and 68.7 m, and eight large box water culverts (C1-C8), with widths ranging from 3.0 to 14.6 m. These sites are representative of many large structures within the study area (Figure 4.4.1, Appendix 7.2.2, and Appendix 7.2.3). We prioritized sites with greater wildlife potential and high proportions of natural area nearby to maximise the chances of mammal detections within structures. Each site had unique features; some included dry ledges, while others were fully covered in water. Combined, these sites represented a variety of structures

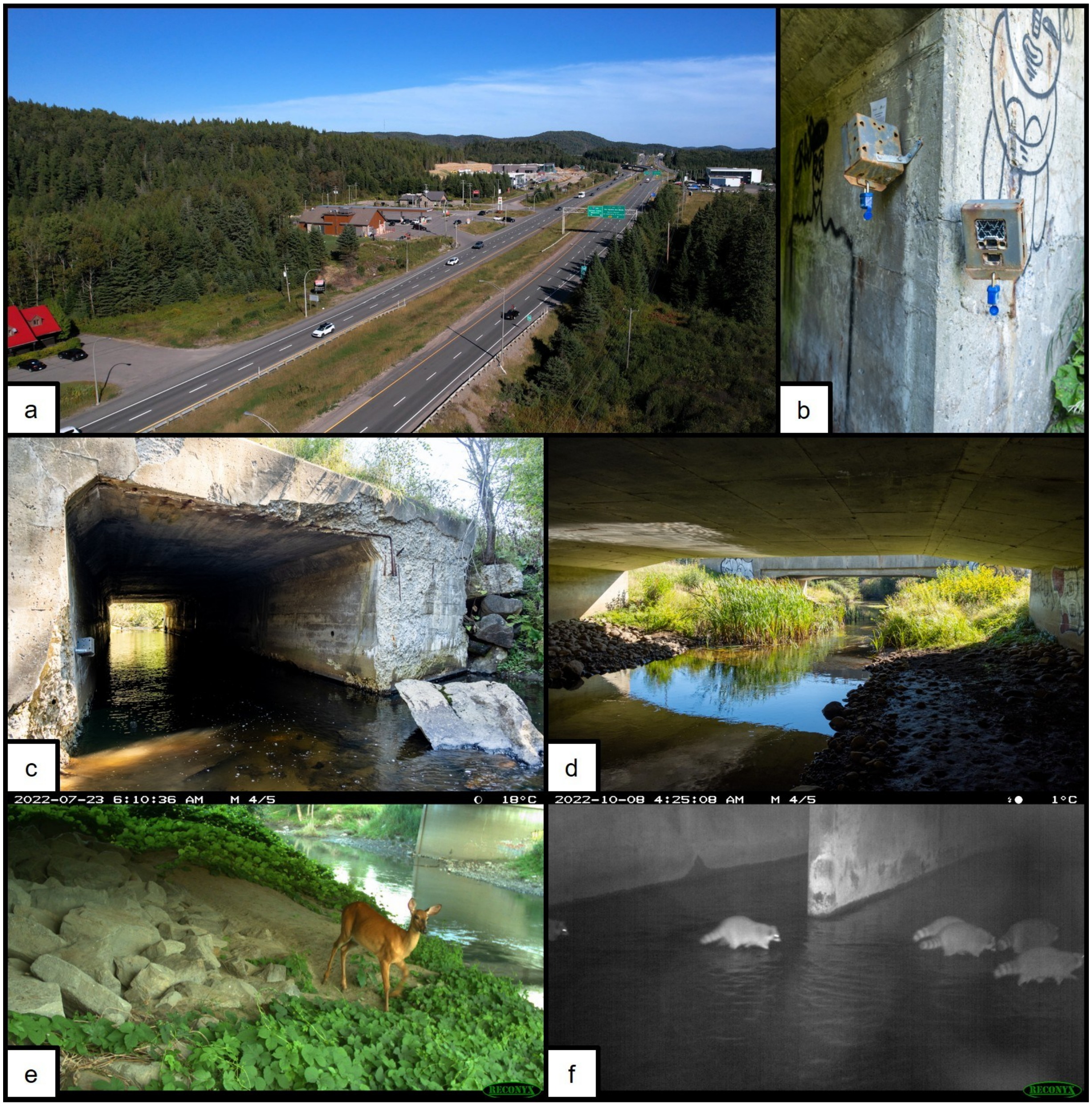

Figure 4.4.1 Overview of sites and mammal detections. (a) Road development over site C3 where A-15 and R-117 merge. (b) Camera placement. (c) Site C2. (d) Inside of site C3. (e) White-tailed deer in site B1. (f) Six raccoons with their paws in water in site C7.

found within the Laurentides, which could potentially have been used by mammals to connect habitats on either side of A-15 and R-117. Six culvert sites had two structures, one for each traffic direction, with a large vegetated median. One culvert with very little water, C1, was a prior cattle passage, although the surrounding area had by then fully regrown. Sites B1 and C2 were located outside of the mapped ecological corridors. Both bridges had a very large opening (width × height), and B1 and B2 north had the widest sand ledges of all sites.

4.4.2 Data collection and processing

4.4.2.1 Trail cameras

To monitor mammals at bridges and water culverts, we mounted four Reconyx Hyperfire HC600 infrared motion-detection trail cameras (sometimes referred to in the literature as "camera traps", hereafter "cameras") to each structure in June and July 2022 and removed them in December 2023 and January 2024 (Figure 4.4.1 and Appendix 7.2.4). The cameras at positions 2 and 3 are considered "inside", monitoring animals within the structures. On site B1, we installed only two cameras facing the inside of the structure because we perceived this site to be of lower ecological interest. Dates when cameras were active were logged to track when cameras malfunctioned and did not take any pictures. The algorithm MegaDetector (MDv5a) and the software Timelapse were used to process and tag pictures (Beery et al., 2019; Greenberg, 2023). We used a 20-minute interval for detections and counted multiple detections if multiple individuals were observed in the same picture. We believed that many animals would spend time in the vegetated medians, justifying this long interval. Different groups of species were created for species that were harder to distinguish. We classed all detections into one of four categories, applying the same criteria as Warnock-Juteau et al. (2022) for "Full crossing" and "Aversion". A mammal detection identified by cameras on either side of the site within the 20-minute interval is called a "Full crossing", while a detection obviously not crossing through is called an "Aversion". The detections leftover were divided into "Observed inside" if they had been captured by an inside camera or "Observed outside" otherwise. We also recorded whether the animal had been swimming at any point. If it had not, we noted whether it had placed at least one paw or hoof in the water. We used this information to group species into a "water-tolerant” category, which was comprised of species often observed in water. We also created two other categories of species: “water-intolerant” for species never or almost never observed in water, and “low-detection” for species with less than 15 detections. Species categorized as “water-intolerant” are not necessarily incapable of crossing water or swimming; rather, they were simply not observed doing so during our study, in clear contrast to “water-tolerant” species, which were frequently observed in water. We also excluded detections where we could not identify the species from our results, except in Table 4.5.2. We used these different categories of species to determine if “water-tolerance” could explain mammal use. We singled out groundhogs (*Marmota monax*), raccoons (*Procyon lotor*), squirrels (*Sciurus carolinensis* and *Tamiasciurus hudsonicus*), and white-tailed deer (*Odocoileus virginianus*) in certain figures because these species accounted for a large proportion of detections, which made it possible to analyse each of these species individually in our averaged generalised linear mixed models (GLMMs) in 4.4.3 Statistical analysis.

4.4.2.2 Track boxes

We evaluated small and medium-sized mammals in the surrounding habitat by installing track boxes in forest patches next to the sites (Figure 4.4.2). For installation and maintenance, we closely followed the method of Brunen et al. (2020) based on Bélanger-Smith (2014). Sites were divided into four quadrants, each with its own track box, totaling four track boxes per site. Each bridge site only had two track boxes, located on the same shore as the cameras. We associated a unique identifier (ID) to each track box made up of its site and its quadrant: next to the northbound or southbound direction of traffic and towards the north or south. The track boxes were installed in a flat patch of forest with a clearing large enough for the box itself and space to perform maintenance at both ends. Track boxes were placed 13 to 35 m perpendicular to the road and 3 to 45 m away from the structure opening, measured parallel to the road. Landowner permission was required to install track boxes in adjacent habitats, but we were unable to obtain permission for sites C2 and C4 in both years and for site C5 in 2023.

Additionally, challenges related to terrain and landowner access resulted in three track boxes being placed farther from the intended sites. These boxes were positioned 34 to 165 m from A-15 or R-117 and 190 to 250 m from the structure opening, measured parallel to the road. Each track box was constructed from three coroplast panels, cut and folded into a tunnel measuring

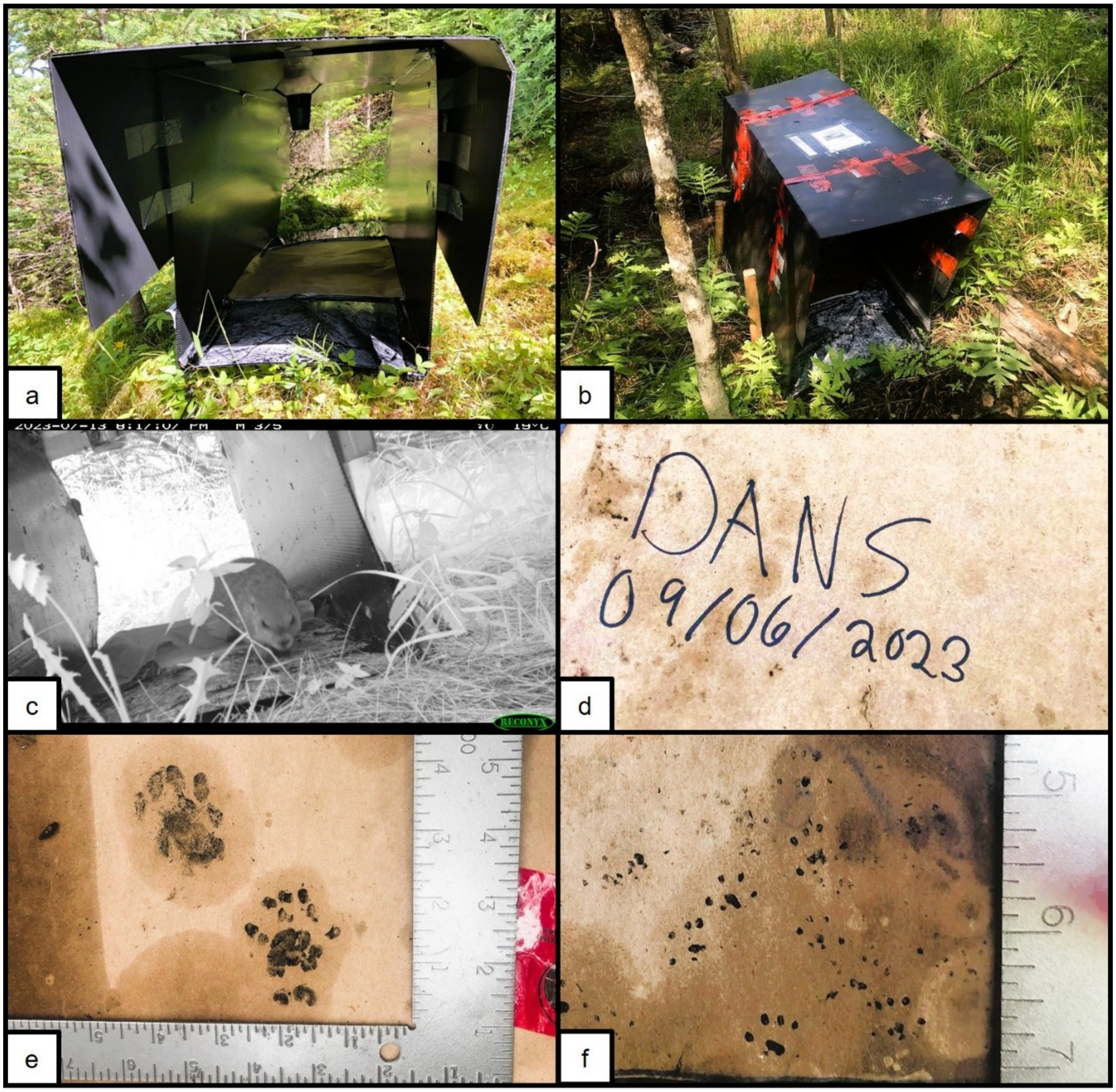

Figure 4.4.2 Track-box data collection. (a) The inside of a track box. (b) A track box in its environment. (c) View of a groundhog inside of a track box. (d) A track-box ID and date (colloquial site name). (e) Domestic cat and groundhog tracks. (f) Mouse or vole tracks.

0.5 m × 0.7 m at the opening and 1.2 m in length. The panels were secured with sheathing tape and stabilized with four stakes anchored in the ground. To attract mammals, we taped a cup of lure to the ceiling made of 60 mL of fish oil, 15 mL of anis oil, and 5 mL of K-9 Triple Take lure (Brunen et al., 2020). To record tracks, we installed a layer of polystyrene on the floor, which was covered by a sheet of kraft paper in the middle, called track paper, and a layer of paint made of 125 mL of charcoal powder stirred into 1 L of mineral oil was applied at both ends.

Each track paper was labelled with its track-box ID and the date of installation. We visited track boxes every two weeks to replace the track paper, reapply paint, and change the lure. If it rained too heavily, which prevented work with the kraft paper and tape used, we rescheduled maintenance to the soonest available date. The track boxes were active from August to November 2022 and May to August 2023. Each year had 5 periods of 2 weeks per track box, totaling 10 track papers per box across two years. For every track paper, we photographed its ID, installation date, and all prints with a square ruler. We compared all mammal prints to those in "Mammal Tracks & Sign: A Guide to North American Species" by Elbroch (2003) and entered data for each track paper into Excel. Species were evaluated on a presence/absence basis as it was not possible to differentiate individuals from the same species. Consequently, the reported numbers by species represent the number of track papers where that species was identified. We grouped certain species with track prints closely resembling one another and kept the same groupings as those we used for camera data.

4.4.3 Statistical analysis

4.4.3.1 Overview of statistical approach

To assess how water-related predictor variables may influence mammal use of bridges and large water culverts, we performed multimodel inference and evaluated interaction effects. We hypothesised that different subsets of species or individual species we detected may be influenced differently by the same predictor variable. From our main dataset containing data related to all species, we created several datasets containing specific species we wanted to evaluate separately, like water-tolerant species and water-intolerant species. We created a global model for each of these separate datasets or separate ways of evaluating these datasets (e.g., different response weights, interaction effects). For each global model, except for models related to interaction effects, we produced GLMMs for every combination of predictor variables, performed model averaging on these lists of GLMMs, and present their resulting coefficients in Table 4.5.3. We illustrate the influence of these coefficients by predicting the response for the global GLMM using the All-Species dataset.

4.4.3.2 GLMM structure

We used this code for the global GLMM for All-Species and modified it by changing the datasets, the fixed effect predictors, or adding an interaction term, based on the way we wanted to estimate the coefficients:

```
Model_Interaction <- glmmTMB(Response ~ (bs(Month, df = 7) + Minimum_water +
                        Water_body_and_wetland_proportion + Water_coverage +
                        Water_flow_average + Opening +
                        (1 | Species) + (1 | Site),
                        offset = log(Camera_days),
                        family = nbinom2,
                        data = Dataset)
```

We utilised R version 4.4.2 and these packages for our analysis: glmmTMB version 1.1.10 and splines to build the global models, performance version 0.12.4 and DHARMa version 0.4.7 for model validation, MuMIn version 1.48.4 for model averaging, and marginaleffects version 0.25.1 for plotting predictions (Arel-Bundock et al., 2024; Bartoń, 2024; Brooks et al., 2017; Hartig, 2024; Lüdecke et al., 2021; R Core Team, 2024).

4.4.3.2.1 Response

We wanted our response variable to maximise full crossings and mammal detections observed inside the sites, allowing us to infer recommendations to increase future mammal use. Other studies using GLMMs for mammal use of structures often only account for full crossings, rates of full crossings, or species detection (Brunen et al., 2020; Denneboom et al., 2021, Jensen et al., 2022). Full crossings were a minority of the mammal detections, but they were the most significant for connectivity, leading us to assign a higher weight to them. Including both detections of species observed inside or outside adds valuable information to our models. Species observed inside were willing to venture into the structures and may have crossed, but our cameras may not have detected them on the other side. Species observed outside show additional species present at these sites, where environmental conditions were suitable for wildlife to discover them. In contrast, we did not include aversions because we did not wish to promote sites at which mammals could be unable to cross. Therefore, we used the following formula for our response variable for every combination of species, site, and month (or period) in our data:

$$Response = 4 \times number\ of\ full\ crossing + 2 \times number\ of\ detections\ observed\ inside + 1 \times number\ of\ detections\ observed\ outside$$

We chose these weights based on comparing the total numbers for each type of detection across all our camera data (Appendix 7.2.8) and our judgment of value for ecological connectivity. For comparison, we also did model averaging on GLMMs for all species combined where all weights were set to one (All-Species weights 1).

4.4.3.2.2 Monthly variation

At most sites, data collection covered 17 full months of data collection (July 2022 – November 2023). We did not include data collected in June 2022, December 2023, nor January 2024 in the GLMMs as those months were largely incomplete. Since our data varied nonlinearly by month (Figure 4.5.3), all GLMMs included a b-spline for month, with a degree of freedom of 7, as this had the lowest corrected Akaike Information Criterion (AICc) (Gurrin et al., 2005; Hurvich & Tsai, 1989). The b-spline accounts for monthly and seasonal variations in mammal activity while ensuring that adjacent months have values more similar to each other than months farther apart. Temperature and precipitation could not be included because they were too collinear with the b-spline for months.

4.4.3.2.3 Predictor variables

We initially used a large set of potential predictors related to structural, landscape, and hydrological characteristics, based on those employed in prior research and our own hypotheses (Bolduc et al., 2025; Denneboom et al., 2021). We then iteratively removed predictors to reduce collinearity, keeping those most relevant to our research questions, until all those left had variance inflation factors below five under all fitted models (Alin, 2010; Brunen et al., 2020; Lüdecke et al., 2021).

Table 4.4.1 presents the definitions of the predictors, and our hypotheses for fixed effect predictor direction. We evaluated the minimum depth of water passing through the sites in September 2023. These water depths varied by ± 5 cm at all other times when we visited the sites, including during and after rainfall, except during winter when the water was frozen, and during a regional flood in April 2023. We evaluated the water coverage in each site by photos taken from cameras 2 and 3, which also confirmed that the water level did not vary outside of this range. We chose to use the opening size, rather than the openness ratio, to have a broader spread of values; we had also hypothesized that the opening size influenced mammal use in our prior study (Bolduc et al., 2025; Denneboom et al., 2021). We did not include the distance to forest as a predictor because all sites were below 18 m, which seemed too low to assess the gap in cover. Because only two of our 11 sites were located outside of ecological corridors (B1 and C2), we could not include this as a predictor variable. We included species and site as random variables, but we did not include species when we analysed a singular species. The track-paper variable was only used in GLMMs with track papers, and the water-tolerance variable was only used in interaction GLMMs.

Table 4.4.1 Predictors used in GLMM analyses.

Predictor	Range (unit)	Definition	Predictor type (prediction)	What does it vary by?
Month	1 – 17	The number for each month with: 1 = July 2022 and 17 = November 2023.	Fixed	Month
Period*	1 – 10	The number of two-week periods during which track papers were deployed.	Fixed	Period
Minimum water depth	0 – 40 cm	The minimum water depth to pass through to be able to cross the site.	Fixed (-)	Site
Water body and wetland proportion	0.000 – 0.355	The proportion of aquatic and humid land cover within a 500-m radius of the site, measured by raster data at 10 m resolution (MELCCFP, 2023c).	Fixed (+)	Site
Water flow average	2.50 – 27.56 m^3/s	The average water flow rate at the Du Nord government hydrological station (MELCCFP, 2025).	Fixed (+)	Month/ Period
Opening	5.4 – 274.8 m^2	The average size of the opening measured as: height × width.	Fixed (+)	Site
Water coverage	0 – 4	The presence of a dry path within the site during the month where: 0 = dry path on both sides, 1 = dry path on both sides becomes dry path on only one side, or reverse, 2 = dry path on only one side, or dry path on both sides becomes no dry path, or reverse, 3 = dry path on only one side becomes no path, or reverse, 4 = no dry path, both sides fully covered in water.	Fixed (-)	Month/ Period and site

Predictor	Range (unit)	Definition	Predictor type (prediction)	What does it vary by?
Track paper*	Month: 0-26 track papers, Period: 0-4 track papers	Monthly data: the total number of track papers with tracks for this species on this site. Period data: the number of track papers with tracks for this species on this site during this period.	Fixed (+)	Month: Site, Period: period
Water tolerance**	0 – 1	Water tolerance of the species where 0 = intolerant and 1 = tolerant.	Fixed (+)	Species
Active camera days	6 – 124 days	The total number of active camera days across all cameras at each site per month/period.	Offset	Month/ Period and site
Species	Up to 14 species	The name of the species or species group.	Random	Species
Site	B1 to C8	The site name.	Random	Site

**Only used for models for research question 3. **Only used for interaction effects models.*

4.4.3.2.4 Offset

We calculated the number of active camera days per month per site and included the logarithm of this value as an offset in the GLMMs. The same was done for period data over those 2-week periods. This offset had a fixed coefficient of one, adjusting the response variable for differences in sampling effort, including camera malfunctions (Espartosa et al., 2011; Rdocumentation, n.d.).

4.4.3.2.5 Family

Our global models showed overdispersion based on a Poisson distribution, requiring a negative binomial type 2 distribution instead. Under this distribution, our models showed no zero-inflation (Zuur et al., 2009).

4.4.3.2.6 Datasets

Only the 14 species with at least 15 detections were included in the models, in accordance with Brunen et al. (2020). Using data collected from cameras, we measured the number of detections of each type (full crossing, aversion, inside, and outside) for each of the 14 species on each of the 11 sites, during each of the 17 months of data collection. We did the same for question 3, where each data point corresponded to a two-week period when track papers were present. The full dataset with 14 species was used for the All-Species GLMMs. We created separate datasets for subsets of species by filtering the overall data by species to see if certain coefficients applied differently to different species, these were: water-tolerant (six species), water-intolerant (remaining eight species), raccoon, white-tailed deer, squirrel, groundhog, species in track papers (eight species), species in track papers evaluated by two-week period matching the track paper deployments (eight species). These four individual species were chosen because they had the most detections which provided enough data points for GLMMs.

4.4.3.2.7 Track-paper particularities

Given that only eight species or groups of species with at least 15 detections by cameras were identified in track papers, not all 14 species could be included in GLMMs if we wanted to include the track paper variable. For research question 3, we evaluated detections both by month and by two-week period matching the track-paper deployments. For data by two-week period, for each data point, we counted the number of track papers at the site during the period with tracks for the species and we excluded sites C2, C4, and C5 from this analysis. For monthly data, we tallied and associated the number of track papers with tracks for each species at each site. Because our sampling effort was only half at sites B1, B2 south, B2 north, and C5, we doubled the number of track papers with tracks for those sites. We removed sites C2 and C4 from this dataset as we did not have track boxes placed there. To account for seasonal changes, we used a b-spline for periods, with a degree of freedom of 3 which produced the lowest AICc on the global model. We expected that data from both August months were more closely related, so we reordered our 10 periods such as periods 1-5 were assigned to May-August 2023 and periods 6-10 were assigned to August-November 2022. The year was not included as a random predictor because it caused singularity.

4.4.3.3 Multimodel inference

For each dataset, an initial global GLMM was produced with all five predictor variables we were evaluating (or six in the case of GLMMs with track papers or interaction). For each global GLMM (except interaction GLMMs), we created a list of GLMMs with every combination of predictor variables. For GLMMs with five predictors, this represented 32 candidate GLMMs each (2^5). Coefficients were calculated by using the shrinkage estimator and the AICc weight of each candidate GLMM to average the coefficients for each list of GLMMs, and weighted R^2 values were calculated (Burnham & Anderson, 2002).

4.4.3.4 Interaction GLMMs

For interaction modelling, we added the water-tolerance predictor to the All-Species dataset, which indicated if the species was classed as water tolerant or not. We show a GLMM where water tolerance is treated as a fixed effect predictor (Main effects only GLMM). The GLMM with an interaction effect (Main and interaction effects GLMM) treats the two groups of species separately and evaluates the difference between the coefficients for each group. Although repetitive, we chose to showcase both the evaluation of the water-tolerant and water-intolerant subsets of species with multimodel inference and the interaction GLMMs for completeness.

4.5 Results

4.5.1 Mammal groups by water tolerance

4.5.1.1 Detections by groups

In the 4,169 mammal detections recorded across 20 species or species groups (Appendix 7.2.6 and Appendix 7.2.8), 487 had at least one paw or hoof in the water or were swimming, representing eight species and 11.7% of all detections (Table 4.5.1).

Table 4.5.1 Mammal species observed at least once in the water with their detections on dry ground, in the water, or swimming.

Species	Latin name	Only on dry ground	Paw or hoof or more in water but not swimming	Swimming	Percent of observations in water of total
Raccoon	*Procyon lotor*	1539	293	25	17.1%
White-tailed deer	*Odocoileus virginianus*	488	29	0	5.6%
Groundhog	*Marmota monax*	426	1	0	0.2%
Muskrat	*Ondatra zibethicus*	66	24	80	61.2%
American mink	*Neovison vison*	105	3	11	11.8%
Beaver	*Castor canadensis*	14	0	17	54.8%
Domestic dog	*Canis Familiaris*	12	3	0	20.0%
Fisher	*Pekania pennanti*	2	0	1	33.3%

The highest percentages of detections in water were recorded for beaver (*Castor canadensis*) and muskrat (*Ondatra zibethicus*) (>50%). In contrast, only one groundhog was observed with at least one paw in the water, compared to 426 detections of groundhogs solely on dry ground. Accordingly, we allocated groundhogs to the water-intolerant species group. Due to the low number of fisher (*Pekania pennanti*) detections, we allocated this species to the low-detection species group. All six remaining species observed in the water more than once were included in the water-tolerant group. These six species were observed much more often in our study than all other 14 species combined, accounting for 65.1% of all detections (Table 4.5.2). Additionally, water-tolerant species showed the highest number of full crossings, with 84.5% of full crossings across all species (raccoons accounted for 61.6% of all full crossings), compared to 15.4% for water-intolerant species. The proportion of detections of the full crossing or observed inside types were highest for water-tolerant species (67.7% when excluding raccoons, 63.3% when including them) than for water-intolerant species (50.1%), a difference of 13% that was statistically significant ($\chi^2 = 64.9$, df = 1, $p < 0.001$).

Table 4.5.2 Detections by water-tolerance group, species, and type of detection.

Group	Species	Latin name	Full crossing	Observed inside	Aversion	Observed outside	Total
Water-tolerant	American mink	*Neovison vison*	9	48	0	62	119
	Beaver	*Castor canadensis*	0	6	0	25	31
	Domestic dog	*Canis Familiaris*	1	2	4	8	15
	Muskrat	*Ondatra zibethicus*	5	46	0	119	170
	Raccoon	*Procyon lotor*	492	649	90	629	1,860
	White-tailed deer	*Odocoileus virginianus*	169	291	24	33	517
	Subtotal		676	1,042	118	876	2,712
Water-intolerant	Chipmunk	*Tamias striatus*	0	10	2	6	18
	Domestic cat	*Felis Catus*	21	47	2	67	137
	Groundhog	*Marmota monax*	63	197	45	122	427
	Hare	*Lepus sp.*	0	2	7	32	41
	Mouse or vole	*Undetermined species*	0	31	1	53	85
	Red fox	*Vulpes vulpes*	9	37	8	35	89
	Squirrel	*Sciurus carolinensis and Tamiasciurus hudsonicus*	28	200	10	276	514
	Stoat or weasel	*Mustela sp.*	2	32	0	10	44
	Subtotal		123	556	75	601	1,355
Low-detection	American marten	*Martes americana*	0	3	0	0	3
	Brown rat	*Rattus norvegicus*	0	0	0	1	1
	Coyote	*Canis latrans*	0	1	0	0	1
	Fisher	*Pekania pennanti*	1	1	0	1	3
	Mustelidae	*Mustelidae*	0	0	0	4	4
	River otter	*Lontra canadensis*	0	2	0	2	4
	Striped skunk	*Mephitis mephitis*	0	4	1	4	9
	Subtotal		1	11	1	12	25
	Unknown species		0	33	0	44	77
	Total		800	1,642	194	1,533	4,169

4.5.1.2 Site use

Water-tolerant and water-intolerant species differed in which sites they were observed at and crossed through (Figure 4.5.1 and Appendix 7.3). Water-tolerant species made full crossings at all sites except C6. Water-intolerant species made full crossings only at six of the 11 sites, and only one full crossing at site B1. Notably, no full crossings were made by water-intolerant species at any of the sites where the minimum depth of water to traverse was above zero.

Four species (groundhog, raccoon, squirrel, and white-tailed deer) accounted for 79.6% of all detections and contributed to 94% of all full crossings (Figure 4.5.2 and Appendix 7.4). White-tailed deer made the majority of full crossings and detections of all types at site B1. Raccoons made the majority of full crossings at sites B2 south, C3, C5, C7, and C8, yet never crossed at the two sites that had the highest water depths (C2 and C6). The highest number of full crossings by water-tolerant species was at B2 south, and all six water-tolerant species were observed at this site, with four species making at least one full crossing. The full crossings made by water-intolerant species are mainly attributed to the species domestic cat (*Felis Catus*) and red fox (*Vulpes vulpes*). The most full crossings and detections of all types for water-intolerant species were seen at B2 north, which had by far the widest sand ledge.

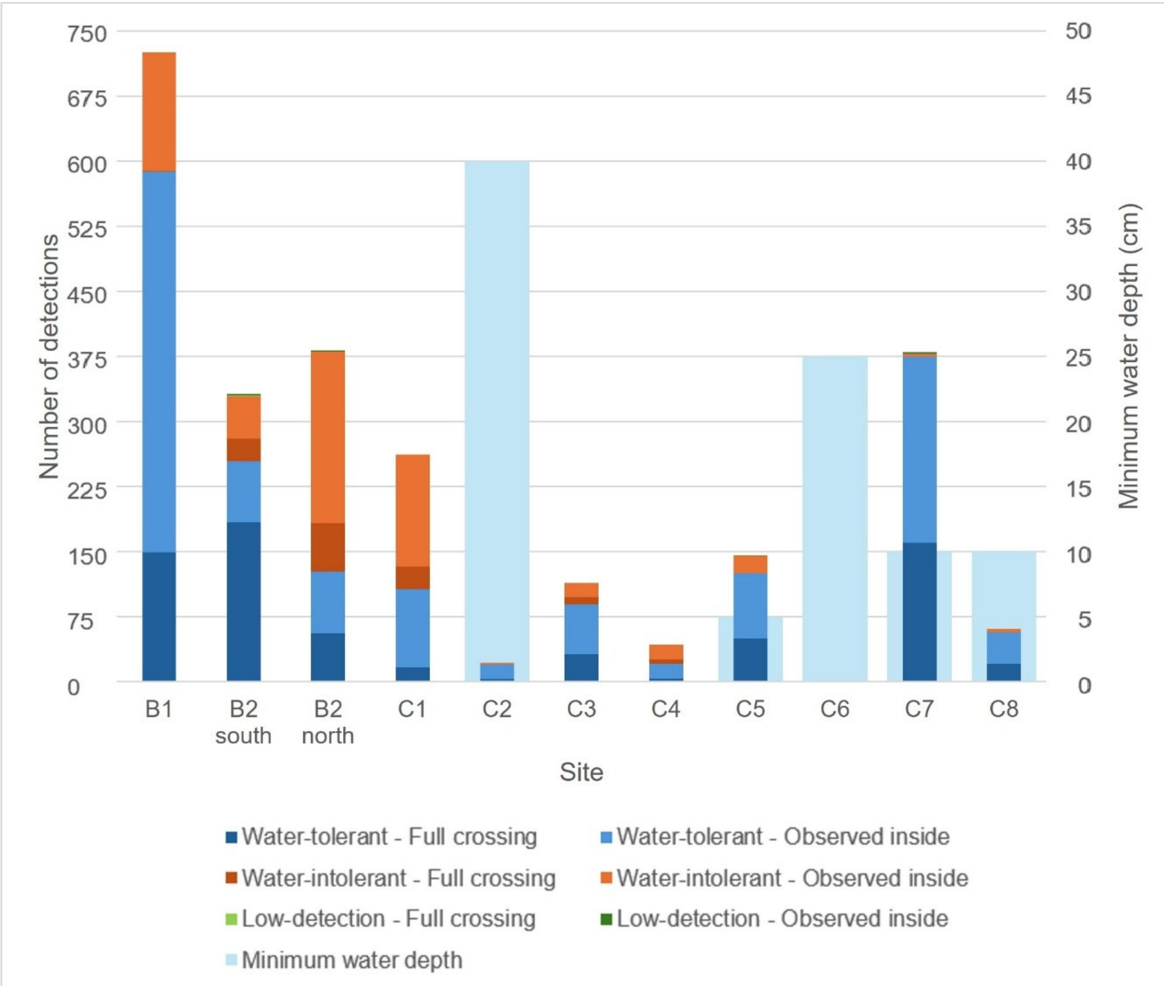

Figure 4.5.1 Full crossings and inside detections by species group and minimum water depth to cross through per site.

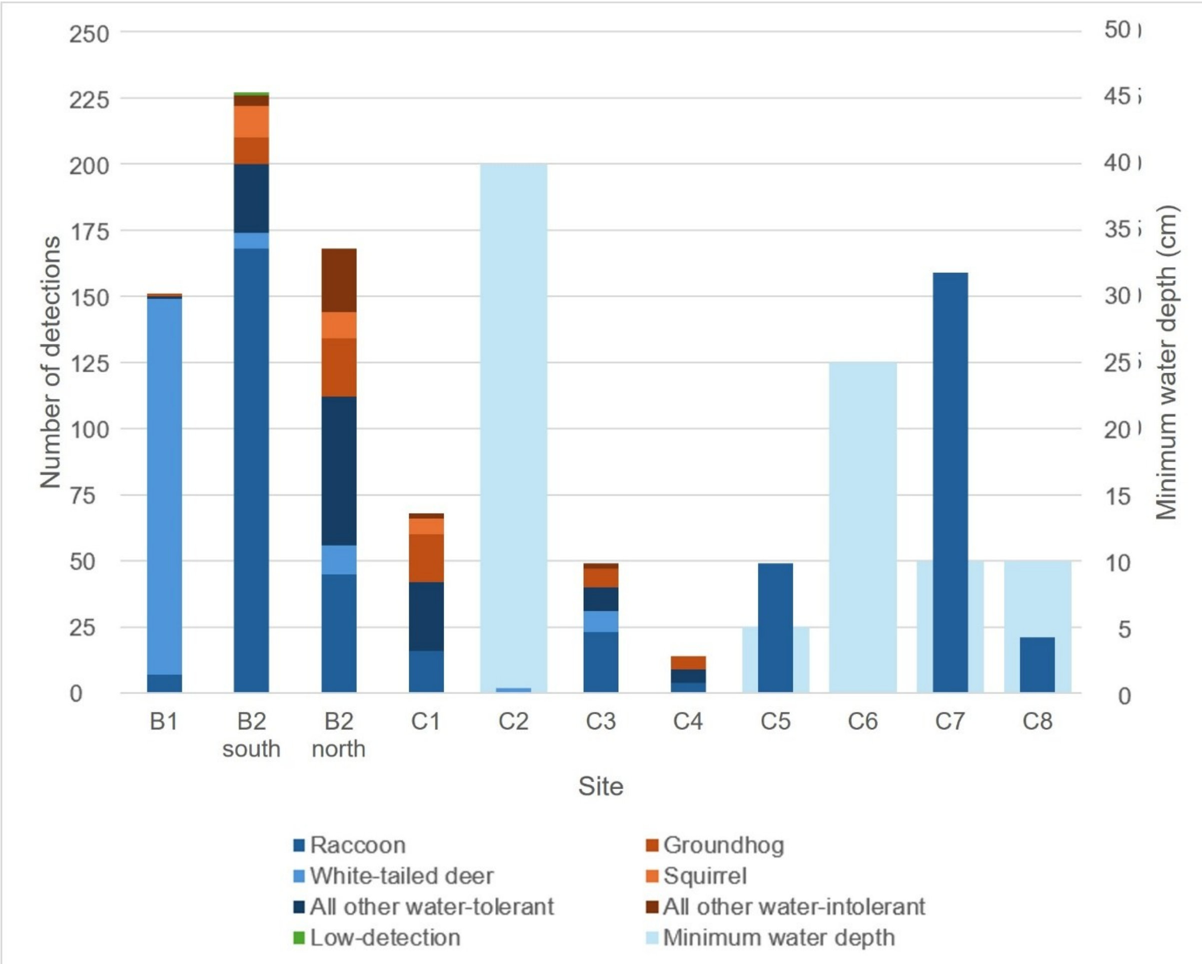

Figure 4.5.2 Full crossings by the four most often detected species overall and minimum water depth to cross through per site.

4.5.1.3 Temporal use

The use of bridges and water culverts varied by group throughout the study period (Figure 4.5.3). Raccoon detections peaked in September 2022, but September 2023 did not show a similar peak. Raccoons, water-tolerant species, and water-intolerant species all showed a minimum number of detections per month during the winter months (December 2022 to March 2023). Water-intolerant species saw their largest peak in May and June 2023, while water-tolerant species (without raccoons) showed their largest peak between September and

November 2022. The spline used for GLMMs (Appendix 7.5) follows a similar monthly pattern to Figure 4.5.3.

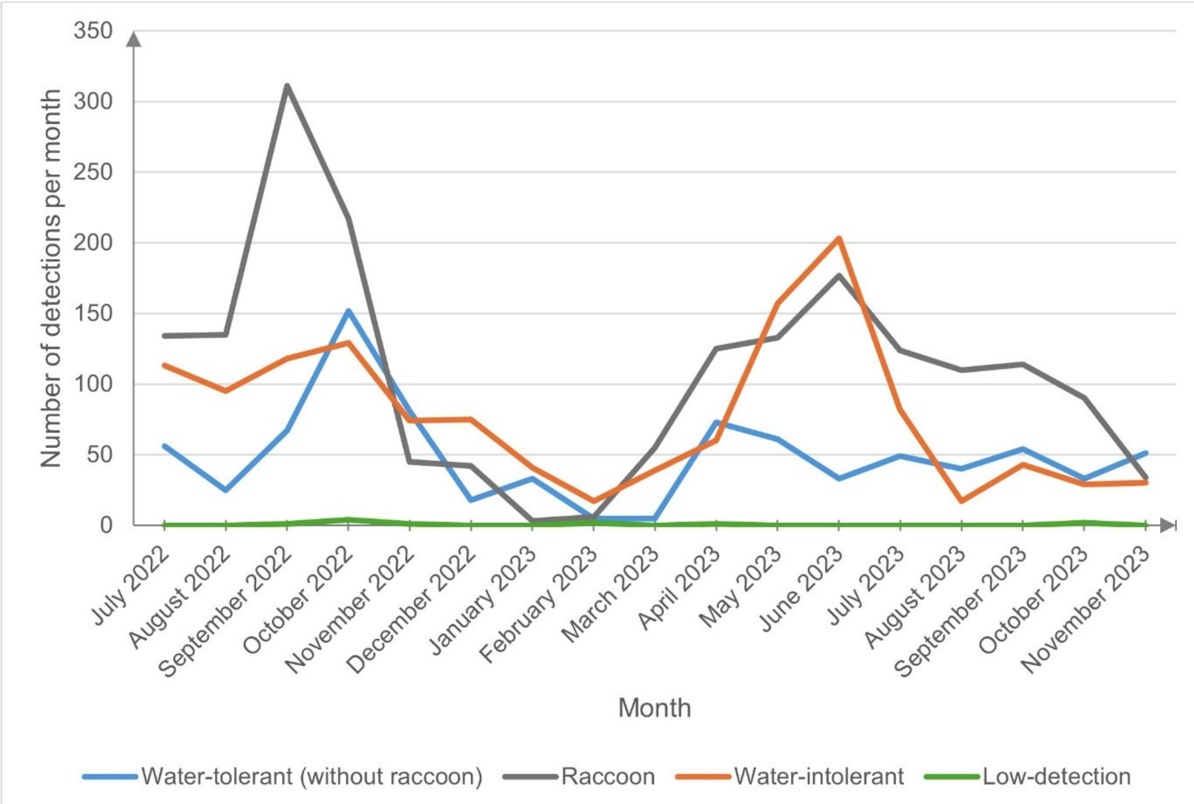

Figure 4.5.3 Detections by species group (water-tolerant [without raccoon], raccoon, water-intolerant, low-detection) per month.

4.5.2 Influence of predictor variables

Table 4.5.3 presents the GLMMs' coefficients, their significance, and their R^2 values for all models evaluated. Appendix 7.6 presents other values associated with these coefficients such as their variance. The minimum water depth was the predictor that was the most often shown as significant in GLMMs, indicating a strong preference for lower water depths in these structures (Figures 4.5.4 and 4.5.5). The minimum water depth affected more negatively water-intolerant species than water-tolerant species, shown both by averaged GLMMs and the interaction effects.

*Table 4.5.3 GLMM(s) coefficients with their significance and R^2. Averaged GLMMs use weighted marginal R^2 and weighted conditional R^2. Significance: ***p < 0.01, **p < 0.05, *p < 0.1.*

Type of GLMM(s)		GLMM(s)	Minimum water depth	Water body and wetland proportion	Water coverage	Water flow average	Opening	Track paper	Water tolerance	Marginal R^2	Conditional R^2
		Coefficient unit	$cm^{-1} \cdot month^{-1}$	$month^{-1}$	$month^{-1}$	$m^{-3} \cdot s \cdot month^{-1}$	$m^{-2} \cdot month^{-1}$	track $paper^{-1} \cdot month^{-1}$	$month^{-1}$		
Global GLMM		All-Species	-0.09 ***	-5.03	0.19 *	0.02	0.00			0.21	0.61
Averaged GLMMs	Group of species	All-Species	-0.08 *	-3.13	0.17	0.01	0.00			0.16	0.62
		All-Species weights 1	-0.06 *	-2.48	0.20 *	0.01	0.00			0.15	0.51
		Water-tolerant	-0.03	-0.08	0.05	0.08 ***	0.00			0.14	0.69
		Water-intolerant	-0.08 **	-6.71	0.03	0.00	0.00			0.22	0.55
	Individual species	Raccoon	-0.02	-0.69	0.02	0.00	0.00			0.37	0.60
		White-tailed deer	0.00	2.11	-0.03	0.00	0.01			0.29	0.90
		Squirrel	-0.03	-2.22	0.01	-0.02	0.01 **			0.41	0.67
		Groundhog	-0.03	-0.82	-0.05	-0.01	0.00			0.78	0.87

Type of GLMM(s)	GLMM(s)		Minimum water depth	Water body and wetland proportion	Water coverage	Water flow average	Opening	Track paper	Water tolerance	Marginal R^2	Conditional R^2
	Coefficient unit		$cm^{-1} \cdot month^{-1}$	$month^{-1}$	$month^{-1}$	$m^{-3} \cdot s \cdot month^{-1}$	$m^{-2} \cdot month^{-1}$	track $paper^{-1} \cdot month^{-1}$	$month^{-1}$		
Averaged GLMMs	Track paper species	With track papers by month	-0.14 ***	-0.39	0.15	0.00	0.00	0.13 ***		0.28	0.74
Averaged GLMMs	Track paper species	With track papers by two-week period	-0.13 **	0.24	-0.02	-0.01	0.00	0.59 ***		0.25	0.77
Interaction GLMMs	Main effects only GLMM		-0.09 ***	-5.05	0.18 *	0.02	0.00		0.96	0.24	0.61
Interaction GLMMs	Main and interaction effects GLMM	Main effects	-0.11 ***	-7.97 **	0.22 *	-0.03	0.00		-0.89	0.26	0.63
		Interaction effects[a]	0.06 ***	7.51 ***	-0.05	0.10 ***	0.00				

[a]Interaction effects were modeled between the species' two water-tolerance groups and all other predictor variables.

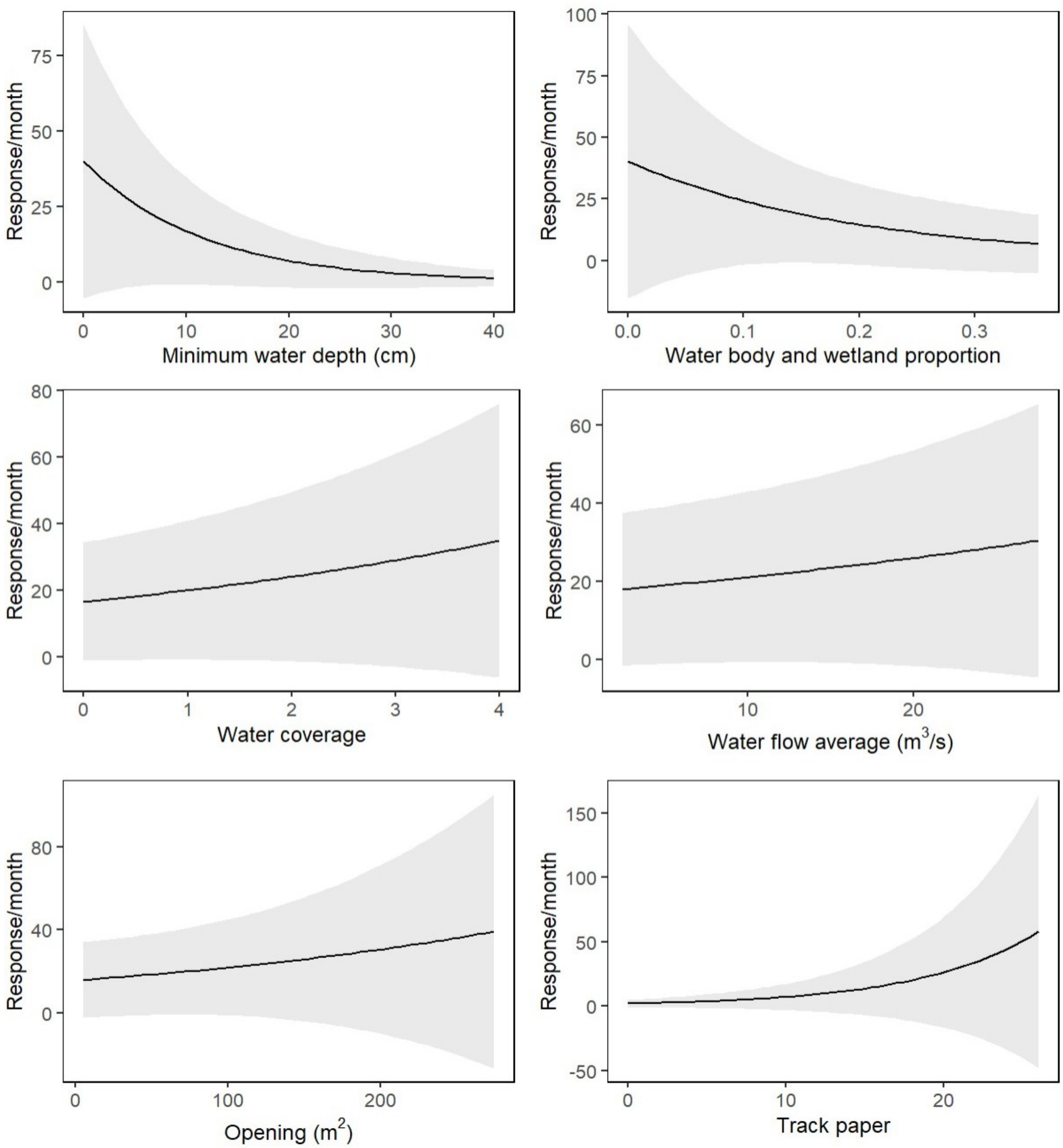

Figure 4.5.4 Predicted response per month for the global GLMM with All-Species by coefficient with a 95% confidence interval in the shaded area. The track-paper coefficient used the global GLMM with species in track papers only (by month).

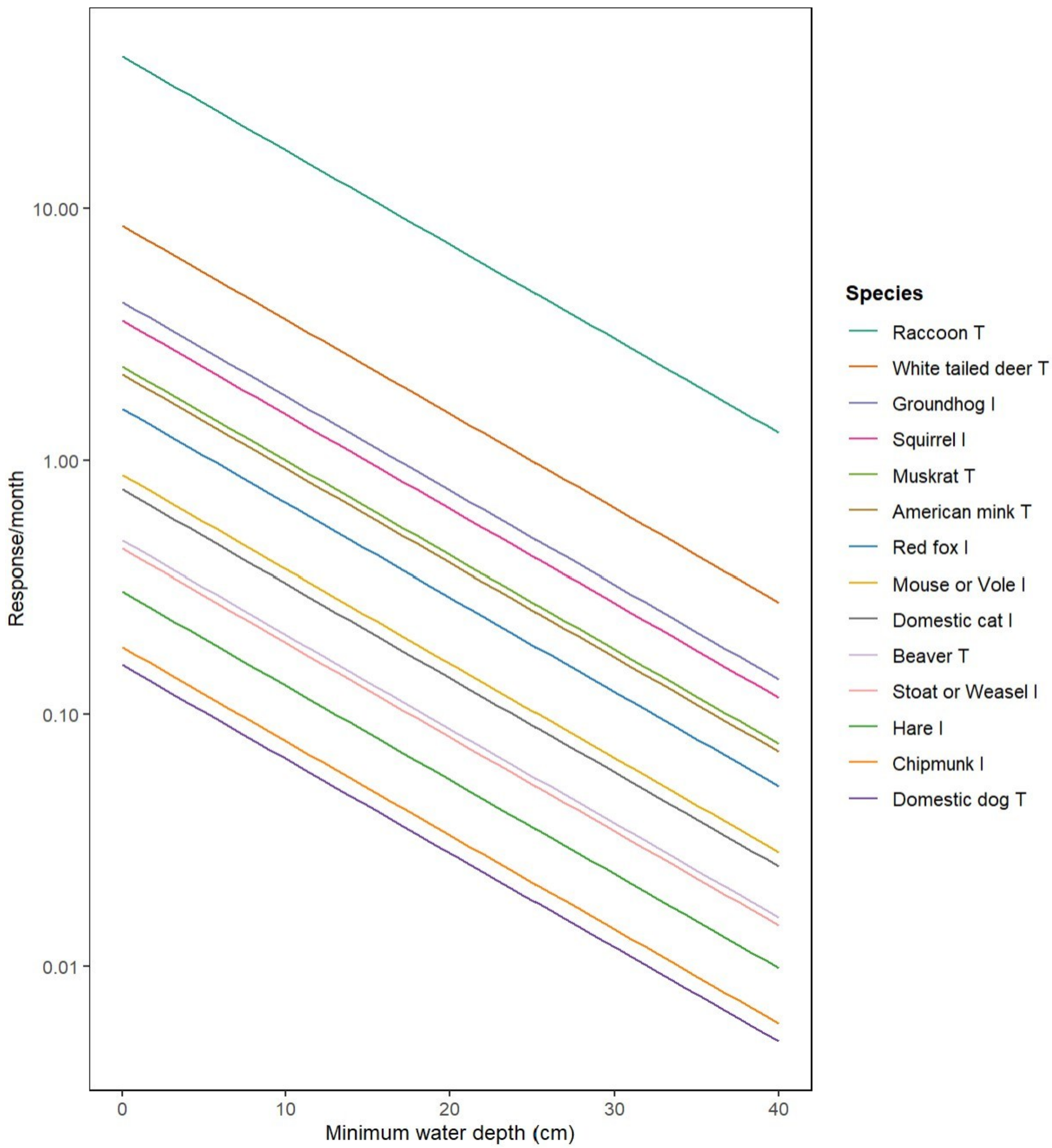

Figure 4.5.5 Predicted response per month for the global model with All-Species for the minimum water depth coefficient separated by species. The Y-axis is on the log scale. The species in the legend are listed in their respective order on the plot. "T" indicates a water-tolerant species, "I" indicates a water-intolerant species.

Higher water body and wetland proportion was only negatively correlated with water-intolerant species use, with a large difference between the coefficients of both groups. All three sites with the lowest water body and wetland proportions (B2 south, B2 north, and C1) were the three sites with the most detections of water-intolerant species.

In contrast to minimum water depth, water coverage was slightly positively related to use of structures. Its significance was higher when all detections were weighted equally (Table 4.5.3 in the All-Species weights 1 averaged GLMM), possibly because full crossings were less emphasized. As a result, species observed inside or outside the structures but possibly deterred from crossing (without being counted as an aversion) due to water were still counted as a positive association.

Average water flow was only significantly associated for water-tolerant species. April and May 2023 exhibited the highest water flow, due to regional flooding, and were associated with a sharp rise in water-tolerant species detections after the low winter months (Figure 4.5.3), while water-intolerant species had a later seasonal rise.

The only species for which the opening size seemed significant was the squirrel, which had most detections at the sites with the largest openings.

Conditional R^2 values, which account for fixed and random effects, were greater in every case than marginal R^2 values, indicating that variation not explained by fixed effects was captured by random effects (i.e., sites and species). The weighted marginal R^2 values, which account only for fixed effects, were all much lower for groups of species than for individual species.

The interaction effects were included to assess if predictor coefficients used in the other GLMMs differed between the water-tolerant and the water-intolerant species groups. The GLMM with only main effects, which treated water tolerance as a fixed effect, had similar coefficient values and significance to the global GLMM as expected, with the addition of the water-tolerance coefficient. In contrast, the GLMM including the main and interaction effects showed that water tolerance does modify the response of species to three specific predictor variables (minimum water depth, water body and wetland proportion, and water flow average), while water coverage did not vary by species water-tolerance and opening size was insignificant.

4.5.3 Small and medium-sized species nearby

Track boxes recorded 457 instances of species presence on 276 track papers in the nine monitored sites (Table 4.5.4). Among these track papers, 48 had no tracks on them (17.4%). Track papers with tracks recorded an average of 2.0 species present. On four track papers, data could not be recovered, so they were excluded from previously mentioned totals. The identified mammal tracks corresponded to ten different species or species groups. Mouse or vole (undetermined species) and chipmunk (*Tamias striatus*) tracks accounted for half (50.5%) of identified presences on track papers. Striped skunk (*Mephitis mephitis*) and American marten (*Martes americana*), each detected fewer than 10 times by cameras, were recorded more often on track papers than by cameras, and their presence was noted at more sites using track papers than cameras. American marten was recorded at four sites by track papers and three sites with cameras, but no site recorded this species using both methods. Site C6, at which no mammals were observed inside or crossing the structure and the number of detections was lowest overall, had a number of presences in track papers similar to other sites with the same number of track papers. The two averaged GLMMs using track papers as a predictor (Table 4.5.3) both showed that the track-paper predictor was highly related to the response measuring species detected by cameras by type of detection. Both GLMMs also had a significant *p* value for the minimum water depth, in accordance with the other multi-species GLMMs presented in the same table.

Table 4.5.4 The total number of track papers with species presence recorded per two-week period, ordered by total number of track papers by species. Positive numbers in bold indicate that the species was not observed at the site by the cameras. Zeros in bold and underlined indicate that the species was observed at the site by cameras but not by track papers.

Species	B1	B2 south	B2 north	C1	C3	C5	C6	C7	C8	Total
Mouse or Vole	**13**	10	7	23	**17**	12	21	**15**	15	133
Chipmunk	**8**	**5**	5	16	**16**	9	**12**	7	**20**	98
Raccoon	5	4	7	7	8	4	11	13	12	71
Groundhog	4	4	4	15	6	5	**7**	6	3	54
Squirrel	2	4	2	11	9	4	**6**	3	5	46
Domestic cat	0	1	3	**3**	0	0	**6**	**4**	**4**	21
Striped skunk*	2	**0**	**1**	**5**	3	**0**	0	**1**	**2**	14
American mink	0	**0**	2	3	2	**0**	**1**	**0**	4	12
American marten*	**1**	**0**	**0**	0	1	**0**	0	**2**	**2**	6
Domestic dog	**1**	**0**	**0**	**0**	1	0	0	**0**	**0**	2
Site total	36	28	31	83	63	34	64	51	67	457
Number of species	8	6	8	8	9	5	7	8	9	10
Number of track papers	19	18	20	40	39	20	39	41	40	276

**Species not used in GLMMs, while all other species in this table were included when modelling with track papers.*

4.6 Discussion

4.6.1 Groups and predictors

Our results showed that only six mammal species often swam or traversed through structures underneath roads while in the water. Water-intolerant species, on the other hand, were never detected crossing structures that had no dry path and were rarely detected inside of these structures. Moreover, our hypothesis was also supported by the statistical analysis, as all species evaluated in GLMMs were more likely to use bridges and water culverts with lower minimum water depth depths. The GLMM coefficients confirmed that water-intolerant species were more strongly deterred by high minimum water depth than their more aquatic counterparts. These findings align with previous studies that determined that higher water depths within culverts result in fewer crossings by mammals, especially by less aquatic species (Brunen et al., 2020; Craveiro et al., 2019; Serronha et al., 2013). Brunen et al. (2020) observed similar mammal species to ours due to the proximity of the study areas but only observed raccoons and American minks crossing frequently through culverts. We saw similar results for our culverts where the minimum water depth was above zero, yet our culverts and bridges with dry paths saw more species cross regularly, especially those water-intolerant. Marangelo (2019) only observed species more tolerant to water cross through box culverts with flat concrete bases which were entirely covered in water. C7 was the only site with this type of base in our study, and only water-tolerant species crossed through it. Sites C3 and C4, which both had 0 cm as the minimum water depth, both required crossing small streams in the ditches to access the sites directly from the closest forested habitat, this also likely limited water-intolerant mammal use.

The minimum water depth, already quite significant, could have been measured more regularly to understand variations within a site, although its average values would likely be similar to the ones used in this analysis. We hypothesize that some mammals may wait for a lower minimum water depth or a lower water flow rate at some sites before crossing. For example, we recorded seven groundhog aversions in nine days in July 2023 in site C7, out of a total of nine detections during this period, and 20 detections during the entire data collection period at this site. These aversions could be from the same groundhog waiting for better conditions before crossing this culvert.

Higher proportions of water bodies and wetlands near sites were negatively associated with use by water-intolerant species. Three of the four sites with the lowest proportions (B2 north, B2 south, C1) were also among the sites where the minimum water depth was 0. Had sites with high proportions of water bodies and wetlands had dry ledges or shelves for water-intolerant species to cross, this negative association may not have been present. Our sites all had a stream or river running through them (except site C1 which had an intermittent stream), and Jensen et al. (2022) found that species richness and detections for some species increased in sites closer to streams.

Serronha et al. (2013) found that culverts with higher water coverage of their base were less used by most species, and we had expected similar results. On the contrary, our coefficients for water coverage were mostly positive. We attribute this to residual seasonal variation not fully captured by the month b-spline, as water coverage values were lower at all sites in winter (due to ice, which we considered "dry ground") and mammal detections were fewer, whereas other seasons showed both higher mammal counts and greater water coverage.

The water flow average by month was not a significant predictor except for water-tolerant species, but its significance might have increased if we had evaluated it at a finer temporal or spatial scale, such as a daily rate or a rate measured at each individual site, since the rate came from a nearby hydrological station (MELCCFP, 2025).

The opening size was not significant to influence the use by most species. For deer, Denneboom et al. (2021) found that height was insignificant, while Jensen et al. (2022) found that openness was significant. Most of our white-tailed deer detections (82.4%) occurred in the bridge sites, which had the largest opening sizes, and the widths of our culverts were larger on average than of those studied by Jensen et al. (2022).

The larger absolute values of the coefficients and the higher weighted R^2 in the All-Species averaged GLMMs, compared to the averaged GLMMs with response weights set to one, can be explained by the All-Species GLMM better capturing the greater variation in response values than the All-Species weights 1 GLMM. As we expected, water-tolerant species and water-intolerant species had the different coefficients and significance for multiple water-related predictors. For species-specific averaged GLMMs, the predictors and random effects (sites) were better at capturing variations in the responses, even when the sample size was much smaller. Variations that exist between these predictor variables indicate that individual species were influenced by different hydrological and landscape site conditions.

The GLMM using only main effects and the water-tolerance predictor as a fixed effect showed similar coefficients and associated significance compared to the averaged GLMM for All-Species. Differences between the averaged GLMMs coefficients using datasets including only water-tolerant and only water-intolerant species were also comparable to those explained by the coefficients of the GLMM with interaction effects. The interaction-effects GLMM highlighted and confirmed that minimum water depth affects both water-tolerant and water-intolerant species negatively, but that water-intolerant species are much more greatly affected. In essence, both the GLMM with interaction effects and the groups of species modelled separately showed the same trends in their coefficients. Using only the approach with the interaction effects would have streamlined our analysis.

Our analysis assumed random intercepts but not random slopes for our coefficients, which is visualised in Figure 4.5.5. It is unlikely that multiple species, even within a water-tolerant or water-intolerant subgroup, would all have the same slopes with these coefficients. We observed this with different coefficient values for individual species compared to groups of species or All-Species. Future research should consider implementing random slopes to account for individual species differences. Thus, analysis of individual species' coefficients could be included in the larger model with more species.

4.6.2 Species found in the surrounding habitat

Overall, track-paper data collection did not reveal any additional species in the vicinity of the existing structures compared to those detected by cameras. Small and medium-sized mammal species and families present in the Laurentides but not detected by either of our methods include the North American porcupine (*Erethizon dorsatum*), shrew, flying squirrel

(*Glaucomys sp.*), and mole (GBIF.org, 2024; iNaturalist, 2024; MELCCFP, 2023a). Other species detected by cameras but not by track boxes were: muskrat, red fox, stoat or weasel (*Mustela sp.*), hare (*Lepus sp.*), North American river otter (*Lontra canadensis*), fisher, and brown rat (*Rattus norvegicus*). Track boxes were too small and not designed to detect large mammals, but we also note that many of these species known to inhabit the Laurentides, and in some cases appearing in road mortality records, were never observed in our camera data: black bear (*Ursus americanus*), bobcat (*Lynx rufus*), Canada lynx (*Lynx canadensis*), moose (*Alces alces*), and wolf (*Canis lupus*) (GBIF.org, 2024; MELCCFP, 2023a; Raibaldi, 2020). In contrast to our track-paper results, Brunen et al. (2020) were able to identify snowshoe hare (*Lepus americanus*), North American porcupine, weasel spp., muskrat, and North American river otter next to their sites using this method. Notably, the three species targeted by the K-9 Triple Take lure: fox, coyote (*Canis latrans*), and lynx (*Lynx sp.*), were not seen in our track papers nor on those of Brunen et al. (2020).

Although presence within the local habitat seems to be an important predictor for mammal use of water culverts and bridges, there was a mismatch between camera detections and track paper identification for multiple species. Mouse or vole and chipmunk, the smallest species in our study, which were also present at all sites according to track papers, may not have been detected by cameras at certain sites due to their small size and camera positioning (Jumeau et al., 2017). The observation of certain species on track papers but not by cameras at specific sites may indicate that these sites or the immediate surrounding habitats have characteristics that deter species from using these structures. Species like striped skunk and American marten, with low numbers of detections by cameras, should be included in areas without detections by cameras in the consideration of mitigation measures targeting connectivity, as the track papers showed that they are often present in the surrounding habitat. In a similar manner, the comparable results in terms of species and counts of mammal presence on track papers between sites showed that there are not fewer species nor is mammal activity lower near sites with lower numbers of camera detections and full crossings, and therefore, they highlight a stronger need for mitigation of these structures in particular to increase their use.

Our results did not align with the ecological connectivity model from Després-Einspenner et al. (2020) that proposed several ecological corridors linking both national parks, which overlapped nine of our eleven sites. First, we only observed two of the five umbrella species of mammals included in the model, specifically white-tailed deer and American marten. Second, we did not observe marked differences for species or detections between the two sites outside of the corridors (B1 and C2) and the sites within, except for more species known to inhabit urban environments in site B1. Importantly, our analysis did not measure mammal movement on the road surface or in the surrounding habitats. The connectivity model was also not designed to capture population density or number of detections (Després-Einspenner et al., 2020; Keeley et al., 2025).

4.6.3 Limitations

We acknowledge several limitations in data collection and analysis. The placement of the cameras at 1.2 m high and only on one side of each site (except B2), and their imperfect detection probability, may have missed mammals, particularly for small species (Jacobs & Ausband, 2018; Jumeau et al., 2017). The water-tolerant mammals are larger on average than their water-intolerant counterparts, which may partly explain their higher number, as they would be better detected by cameras. However, this does not explain the differences between their use of different sites.

Extending the study to more sites and a longer duration would improve inference about the influence of predictors variables and rarely observed species. Additionally, this would help explain the yearly variation in summer and fall data. The scope of this study was also limited by the lack of experimental modifications. At present, our results cannot be compared to structures designed with wildlife movement as the primary goal as there are none in the study area

(Rytwinski et al., 2015). We only evaluated track-box data during the months of May-November, which may have missed several species because of seasonal variations in mammal activity (Caravaggi et al., 2018). Small and medium-sized mammals that were not identified by our track boxes may also have been present within the landscape but were not attracted by the lure.

The lack of certain species within our overall data lends credence to the lack of connectivity due to A-15 and R-117. Although road mortality hotspots and possible mitigation measures have been identified for a few species on A-15 and R-117, these should be evaluated in the context of bridges and certain large water culverts potentially providing suitable wildlife passages to mammals if mitigated properly (Lemieux, 2018; Raibaldi, 2020). The frequent use of some sites by some species indicates that the best current unmitigated structures are beneficial for mammal movement and connectivity, but we are under the impression that many of the detections came from the same individuals. In particular, we observed families of white-tailed deer and raccoons with the same number of juveniles repeatedly passing through the same sites within the same season. Similarly, the domestic cat detections at B2 north, which had a few unique coat colours, likely were of the same few individuals.

4.7 Conclusion and recommendations

Across the 11 sites, we observed 20 different mammal species or species groups, 11 of which made at least one full crossing. These species varied in the frequency at which they were detected in the water. By accounting for this trait, this study provides a better understanding of the use of large water culverts and bridges within the Laurentides by various mammal species in relation to their predisposition at entering in water to cross unmitigated structures. We evaluated the influence of predictor variables and recorded small and medium-sized mammals located within the surrounding habitat. We discovered that use of these structures is strongly influenced by species' propensity to cross or swim through water, or water tolerance. Specifically, water-intolerant species almost exclusively used structures with dry paths to cross, as no mammals from species of this category made a full crossing at a site with a minimum water depth above 0 cm and very few were observed inside of these sites. More water-tolerant species, especially raccoons, crossed shallow depths of water (≤ 10 cm), but high water depth was still a very limiting factor. As anticipated, this group was also detected much more frequently in and around water culverts and bridges. Other water-related predictors, namely proportion of water body and wetland around the sites, water coverage, and average water flow, were much less influential on mammal use. Given these findings, we strongly recommend increasing the width of these structures to provide a dry path, ideally on both sides, as this would allow use by water-intolerant species and higher use by water-tolerant species. At sites where widening is not possible, an alternative mitigation measure is to install shelves, which would likely increase movement for small and medium-sized species (Niemi et al., 2014; Villalva et al., 2013). We very strongly recommend the installation of wildlife fencing with an appropriate length to funnel mammals towards these structures and keep them off the roadway (Plante et al., 2019; Rytwinski et al., 2016; Wilansky & Jaeger, 2024). This study should be repeated after the fences are installed to understand the effects of this new mitigation measure on mammal crossings. Future research in other locations should also consider mammal water tolerance when evaluating the effectiveness of these types of structures for their potential as wildlife passages.

The use of weights to multiply the detections by type and sum them to create a single response variable was a novel technique which allowed us to incorporate more wildlife data for the GLMMs and broaden the interpretability of the resulting coefficients. Had we included only the 800 full crossings, analyses would have been limited to the five species with at least 15 detections of this type, compared to the 14 species used in the All-Species GLMMs. Instead, 1,642 detections inside and 1,533 detections outside the sites could be included without overshadowing the significance of the full crossings by using these weights. Future studies using cameras at wildlife passages and unmitigated structures should consider using this system to maximise both the data and species included in GLMMs. Different weights may be appropriate based on specific context (e.g., full crossings are much more important than animal detections) and proportion of detection types (e.g., the rates of full crossings and aversions are much higher or much lower).

Our track-paper data highlighted the advantage of considering mammal presence in the surrounding habitat when evaluating camera data coming from bridges and water culverts. We identified up to four mammal species in the surrounding habitat at each site which were not detected by the cameras at those same sites, possibly due to unsuitable site or habitat conditions or small size (Jumeau et al., 2017). Track paper data also confirmed that, compared to more frequented sites, sites with fewer detections or fewer full crossings recorded similar species and counts of tracks on track papers, meaning that the surrounding habitat was not responsible for the lack of mammals in the structures. Observed species tracks were also a strong predictor for species observed by cameras. We recommend that the evaluation of mitigation measures pertaining to these structures should include all mammal species in the surrounding landscape, as should be the case in the Laurentides.

Although some water culverts and all bridges were used by both water-tolerant and water-intolerant mammals, it appears that the many large water culverts without dry paths do not mitigate at all the loss of mammal movement caused by roads, similar to the results reported by Soanes et al. (2024). Unfortunately, the alternative options for many species remain attempting to cross these busy roads or avoiding these roads entirely, which implies that connectivity in this region is broken. We urge transportation agencies, including the MTMD, to follow the recommendations given above, as well as those from related studies about road ecology in the Laurentides and about culverts in other regions (Drasher & Murdoch, 2021; Paemelaere et al., 2023). Transportation agencies should improve their environmental and ecological connectivity efforts, considering that all but one of these structures were built between 1942 and 1978, when no environmental impact assessments were required. Additionally, along A-15 and R-117, no mitigation measures whatsoever have been implemented retroactively, except for one small naturalisation project spearheaded by conservation organisations (Bouvier et al., 2006; Impact Assessment Agency of Canada, 2023; Nature Conservancy of Canada, n.d.).

5 Thesis Conclusion

In my first manuscript, I assessed the current mammal use of two unmitigated bridges and eight large water culverts in the Laurentides. By using cameras, I identified 20 different species or groups of species of mammals located in or around these sites. Of these, only 11 species crossed at least once through one of the sites. The most prevalent species in descending order were raccoon, white-tailed deer, squirrel (*Sciurus carolinensis* and *Tamiasciurus hudsonicus*), and groundhog (*Marmota monax*), and these accounted for 79.6% of all detections. These species were expected according to similar research in regions nearby. Mammal use varied greatly between sites, bridge sites had many more full crossings and detections than culvert sites, except for C7, which was dominated by raccoons. In this manuscript, I hypothesized that the minimum water depth that animals would need to walk or swim through to be able to cross a site was responsible for lower numbers of full crossings. At site C2, with the highest water depth (40 cm), only 3 full crossings were recorded, and site C6, with the second highest depth (25 cm), was the only site without any full crossings and where no mammal was ever observed inside the structure. All bridge sites had continuous dry ledges, whereas culvert sites had either continuous dry ledges, disjointed dry ledges where the minimum water depth to cross was above 0 cm, or no dry areas within the structures. Notably, I determined that many important mammal species present in the Laurentides were not observed at my research sites. Black bear (*Ursus americanus*), moose, and porcupine (*Erethizon dorsatum*) have been reported in road mortality data in the Laurentides (iNaturalist, 2024; Raibaldi, 2020) but were never observed in this study. These three species and bobcat were also identified in or around similar unmitigated structures in Vermont and in the Eastern Townships (Brunen et al., 2020; Marangelo, 2019; Warnock-Juteau et al., 2022). These missing species should be investigated to determine the causes for their lack of detection; their absence also adds credence to the lack of connectivity for these species, especially those with large home ranges, in the vicinity of A-15 and R-117.

In my second manuscript, I evaluated multiple predictors that influence the use of unmitigated structures. Six species were often observed in the water: American mink (*Neovison vison*), beaver (*Castor canadensis*), domestic dog, muskrat (*Ondatra zibethicus*), raccoon, and white-tailed deer. These were the only species that crossed through sites where the minimum water depth was above 0 cm. Water depth was the most significant predictor among all evaluated to deter mammal use, and also negatively affected water-tolerant mammals.

Overall track-box data in the surrounding landscape showed species also identified in overall camera data, and multiple species, namely mouse or vole, chipmunk (*Tamias striatus*), striped skunk (*Mephitis mephitis*), and American marten, were observed in the vicinity of more sites by track boxes than by cameras directly at the sites. At sites where fewer full crossings or detections were recorded, particularly site C6, similar numbers of species on track papers and identified tracks on them were recorded compared to other sites, meaning that the surrounding habitat was not responsible for the lower mammal use at certain sites. The number of track papers in which a species was observed at a specific site was a strong predictor for the response variable measuring mammal use of the site by cameras for both the averaged GLMM using monthly camera data and the one using camera data that matched the two-week periods when the track boxes were active.

In summary, this research shows that among the 20 species and groups of species observed, four mammal species frequently crossed a few of the sites, another seven were observed crossing at least once through an unmitigated structure, and the remaining nine were detected in or around the sites. While bridges were adequate structures for several mammal species to cross under roads, many mammal species present in the area do not use them. The general low usage of culverts compared to bridges shows that these structures are much less than adequate at providing a linkage between habitats on either side of A-15 and R-117.

Culverts without dry ledges prove to be the least effective in terms of providing connectivity, as structures with the highest minimum water depth were the least used or never used. My results agree with those of prior studies that found that the lack of a dry pathway significantly reduced full crossings by mammals (Brunen et al., 2020; Craveiro et al., 2019; Serronha et al., 2013).

Structures should be oversized so that the stream or river going through them is not as wide as the structure opening, leaving dry paths on either side. This would accommodate larger species as well, which cannot fit on shelves. This would also mitigate increased water flow from greater precipitation and extreme weather events more likely to happen because of climate change (Stott, 2016). Furthermore, I echo the strong recommendation of other studies to add dry ledges or shelves in culverts to increase the use by mammals if such wider structures are not implemented, especially those that proved to be water-intolerant within my results (see Jaeger et al., 2019 and Trocmé & Righetti, 2012 for examples). Wildlife fencing, long enough to prevent the fence-end effect, also needs to be added along all roads where road mortality is present and where population recovery could benefit from fencing, with a priority given to areas where wildlife passages, bridges, and large water culverts are adequate for mammals to cross (Huijser et al., 2016; Jaeger et al., 2019; Lafrance & Alain, 2019; Plante et al., 2019; Wilansky & Jaeger, 2024). This would guide animals towards the structures and reduce road mortality. I observed this road mortality several times during my field days where carcasses of small and medium-sized mammals were located near or directly above my research sites on A-15 and R-117. These suggested mitigation measures represent the most cost-effective ways to increase mammal movement across A-15 and R-117 and reduce road mortality. Ideally, dedicated wildlife passages and long stretches of wildlife fencing should be installed along this road axis (Lemieux, 2018; Raibaldi, 2020). These should be targeted particularly towards species known to be in the area but not currently using unmitigated structures to restore their movement in the Laurentides.

For the Laurentides region, and Quebec in general, I strongly recommend including the potential for bridges and water culverts to serve as wildlife passages in mitigation measure planning by the MTMD by properly retrofitting them. Integrating ecological connectivity was added by the MTMD to their sustainable development action plan in February 2025 (MTMD, 2025a). Transportation agencies in other provinces and countries should also consider how structures within the roadway may impact mammal connectivity. Species, landscapes, and structure types may differ, but providing a dry pathway within these structures will likely increase the number of species which can use existing structures to cross roads, particularly among water-intolerant species. Accordingly, modifying unmitigated current and new structures would greatly benefit connectivity at a lower cost than constructing dedicated wildlife passages (Raibaldi, 2020). In regions without regular wildlife passages, systematically mitigating existing structures like water culverts and bridges can provide a network of safe opportunities for mammals to cross roads (Seiler & Olsson, 2010). For species not observed in my research, dedicated mitigation measures to ensure the viability of the populations of these species should be added. Finally, I urge all levels of government and organisations to limit urban sprawl and habitat fragmentation which threaten connectivity in the Laurentides (Cole, Kross, et al., 2023). Road mitigation measures should not be limited to newly constructed roads, as important ecological corridors are currently bisected by A-15 and R-117 and unmitigated water culverts are broadly ineffective at preventing or reducing the loss in connectivity that has already happened in this region (Després-Einspenner et al., 2020).

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7 Appendices

7.1 Nombre de détections par espèce, type de détection et site.

Espèce	Type de détection	B1	B2 sud	B2 nord	C1	C2	C3	C4	C5	C6	C7	C8	Total
Belette ou hermine *Mustela sp.*	Traversée complète				2								2
	Observé à l'intérieur				32								32
	Non-traversé												0
	Observé à l'extérieur				5	1					3	1	10
Campagnol ou souris espèce indéterminée	Traversée complète												0
	Observé à l'intérieur		7		8			1	15				31
	Non-traversé					1							1
	Observé à l'extérieur		16	11		1			22	2		1	53
Castor *Castor canadensis*	Traversée complète												0
	Observé à l'intérieur		1				2		2			1	6
	Non-traversé												0
	Observé à l'extérieur			2		2		12	1			8	25
Cerf de Virginie *Odocoileus virginianus*	Traversée complète	142	6	11		2	8						169
	Observé à l'intérieur	228	2	9		10	39	2				1	291
	Non-traversé	8	2		1		9			2	1	1	24
	Observé à l'extérieur		12	6		1	13				1		33
Chat domestique *Felis catus*	Traversée complète		1	20									21
	Observé à l'intérieur			46		1							47
	Non-traversé			2									2
	Observé à l'extérieur		1	66									67

Espèce	Type de détection	B1	B2 sud	B2 nord	C1	C2	C3	C4	C5	C6	C7	C8	Total
Chien domestique *Canis familiaris*	Traversée complète						1						1
	Observé à l'intérieur			1			1						2
	Non-traversé										4		4
	Observé à l'extérieur		1		1		1				2	3	8
Coyote *Canis latrans*	Traversée complète												0
	Observé à l'intérieur	1											1
	Non-traversé												0
	Observé à l'extérieur												0
Écureuil *Sciurus sp.*	Traversée complète		12	10	6								28
	Observé à l'intérieur	41	13	106	31			3	4			2	200
	Non-traversé		2	2	3						1	2	10
	Observé à l'extérieur		26	205	5	6	1	3	7		14	9	276
Lièvre *Lepus sp.*	Traversée complète												0
	Observé à l'intérieur	1			1								2
	Non-traversé							1	6				7
	Observé à l'extérieur							6	26				32
Loutre de rivière *Lontra canadensis*	Traversée complète												0
	Observé à l'intérieur										2		2
	Non-traversé												0
	Observé à l'extérieur					1				1			2

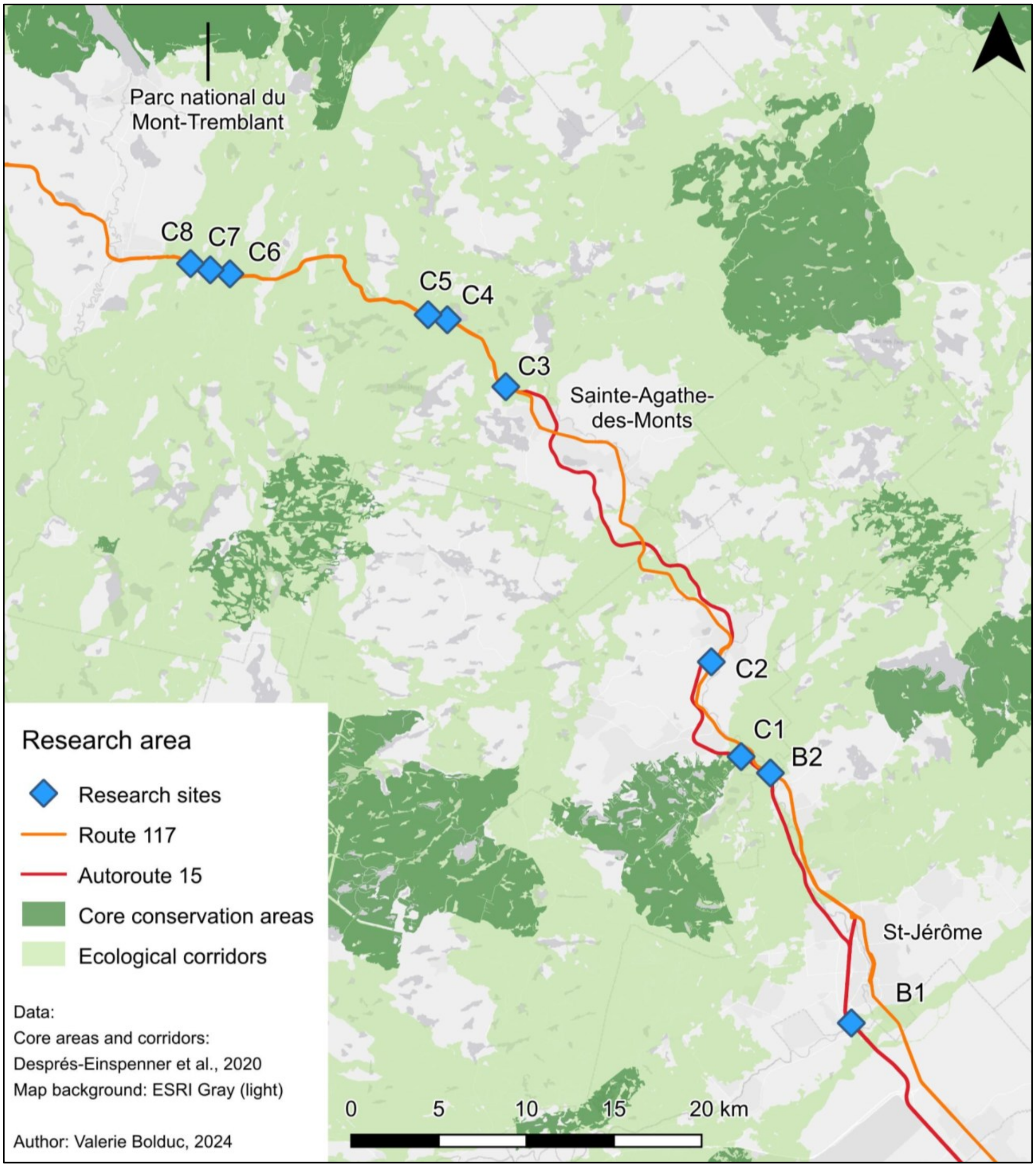
Espèce	Type de détection	B1	B2 sud	B2 nord	C1	C2	C3	C4	C5	C6	C7	C8	Total
Marmotte *Marmota monax*	Traversée complète	1	10	22	18		7	5					63
	Observé à l'intérieur	73	24	36	37		12	12			3		197
	Non-traversé			6	6	4	1				8	20	45
	Observé à l'extérieur		13	40	14	15	5	4	2		9	20	122
Martee d'Amérique *Martes americana*	Traversée complète												0
	Observé à l'intérieur		1	1					1				3
	Non-traversé												0
	Observé à l'extérieur												0
Moufette rayée *Mephitis mephitis*	Traversée complète												0
	Observé à l'intérieur	4											4
	Non-traversé						1						1
	Observé à l'extérieur		1				1		2				4
Mustelidae	Traversée complète												0
	Observé à l'intérieur												0
	Non-traversé												0
	Observé à l'extérieur				1				1		1	1	4
Pékan *Pekania pennanti*	Traversée complète		1										1
	Observé à l'intérieur		1										1
	Non-traversé												0
	Observé à l'extérieur		1										1

Espèce	Type de détection	B1	B2 sud	B2 nord	C1	C2	C3	C4	C5	C6	C7	C8	Total
Rat surmulot *Rattus norvegicus*	Traversée complète												0
	Observé à l'intérieur												0
	Non-traversé												0
	Observé à l'extérieur			1									1
Rat musqué *Ondatra zibethicus*	Traversée complète		2		1	1			1				5
	Observé à l'intérieur		2	1	9	4	3	6	21				46
	Non-traversé												0
	Observé à l'extérieur		6	9		41	1	5	18		2	37	119
Raton laveur *Procyon lotor*	Traversée complète	7	168	45	16		23	4	49		159	21	492
	Observé à l'intérieur	197	59	59	57	2	10	4	25		209	27	649
	Non-traversé	6	17	4	11	20	1		7	4	5	15	90
	Observé à l'extérieur		208	117		57	44	4	9	26	113	51	629
Renard roux *Vulpes vulpes*	Traversée complète		3	4			2						9
	Observé à l'intérieur	20	1	7	3	1	3	1				1	37
	Non-traversé	1	5				2						8
	Observé à l'extérieur		14	12			9						35
Tamia rayé *Tamias striatus*	Traversée complète												0
	Observé à l'intérieur			1	8				1				10
	Non-traversé					2							2
	Observé à l'extérieur			1		2			2		1		6

Espèce	Type de détection	B1	B2 sud	B2 nord	C1	C2	C3	C4	C5	C6	C7	C8	Total
Vison d'Amérique *Neovison vison*	Traversée complète		8								1		9
	Observé à l'intérieur		5		14	1		5	22			1	48
	Non-traversé												0
	Observé à l'extérieur		17	1	2	14	2	3	4		14	5	62
Espèce inconnue	Traversée complète												0
	Observé à l'intérieur	5	4	2	3		1	3	6		8	1	33
	Non-traversé												0
	Observé à l'extérieur		6	10	1	3	2	4	5	3	5	5	44
Total	Traversée complète	150	211	112	43	3	41	9	50	0	160	21	800
	Observé à l'intérieur	570	120	269	203	19	71	37	97	0	222	34	1,642
	Non-traversé	15	26	14	21	27	14	1	13	6	19	38	194
	Observé à l'extérieur	0	322	481	29	144	79	41	99	32	165	141	1,533
	Toutes détections	735	679	876	296	193	205	88	259	38	566	234	4,169
Nombre d'espèces	Traversée complète	3	9	6	5	2	5	2	2	0	2	1	11
	Observé à l'intérieur	8	11	10	10	6	7	8	8	0	3	6	19
	Non-traversé	3	4	4	4	4	5	1	2	2	5	4	11
	Observé à l'extérieur	0	12	12	5	11	9	7	10	3	9	9	18
	Total	8	14	14	12	13	10	10	11	4	10	11	20

7.2 Translated French manuscript figures, table, and appendix

7.2.1 Map of the Laurentides: research sites, core conservation areas, ecological corridors and roads.

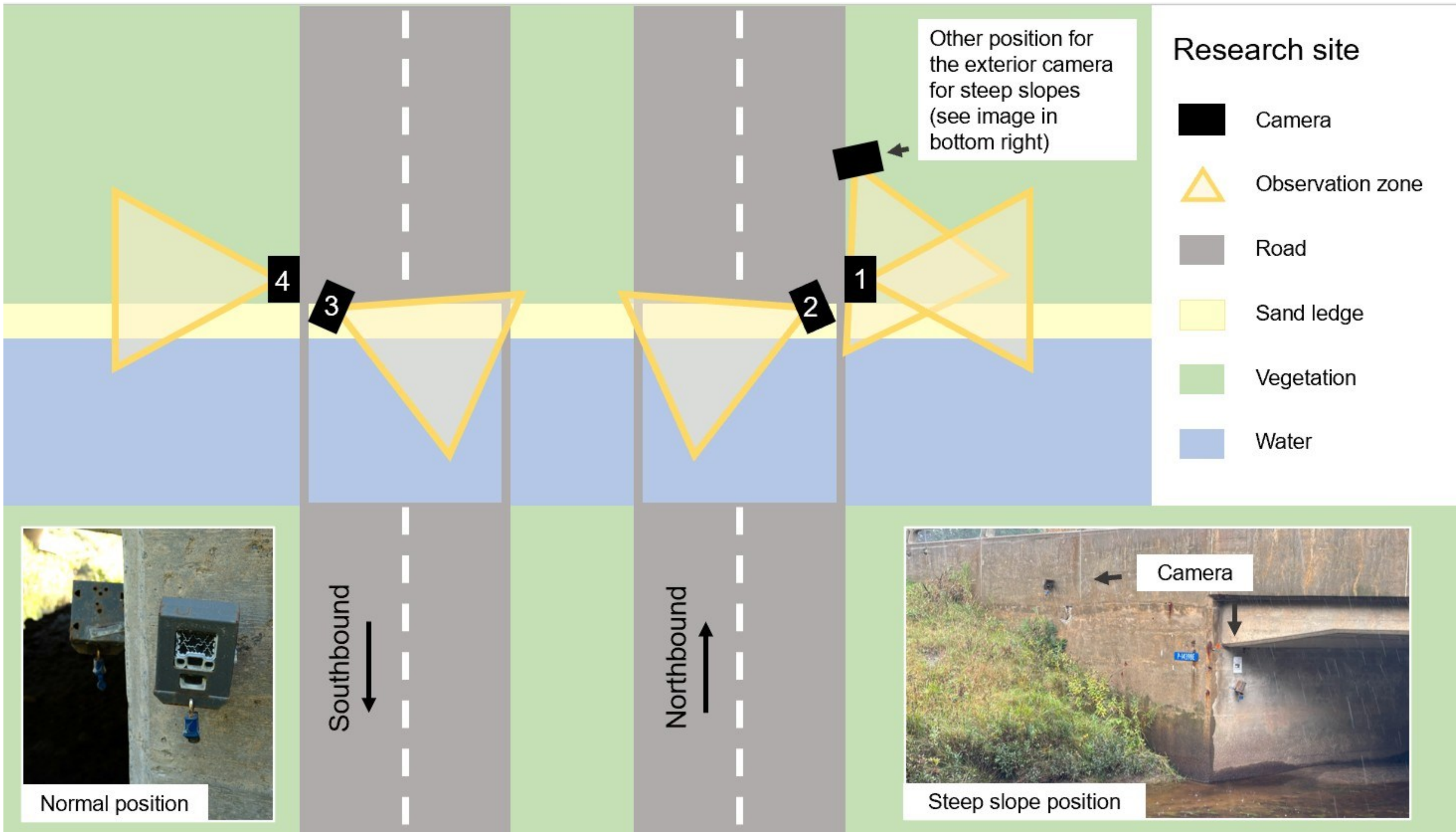


7.2.2 Photos of the research sites (B = bridge, C = culvert).

7.2.3 Geographic, physical, and environmental characteristics of each site. Annual average daily traffic (AADT) comes from (MTMD, 2023d). For the sites with two structures: data for height, width, and length are an average of the values for both structures. These values and the construction year were provided directly by the MTMD. Sites with two construction years are because the secondary structure was added at a later date.

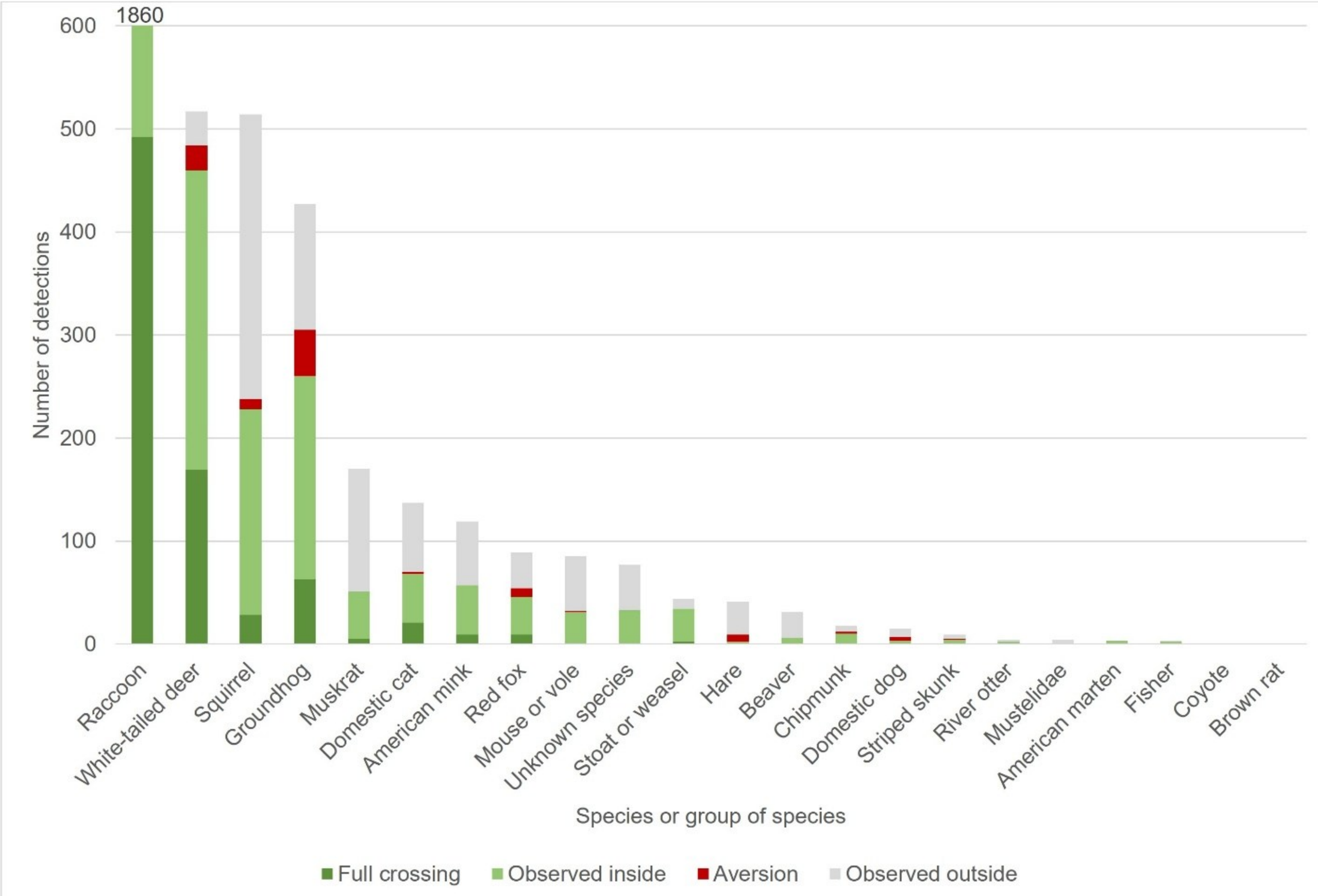
	Unit	B1	B2	C1	C2	C3	C4	C5	C6	C7	C8
Latitude	° North	45.7533	45.8780	45.8852	45.9325	46.0653	46.0970	46.0984	46.1110	46.1124	46.1148
Longitude	° West	-74.0150	-74.0891	-74.1113	-74.1385	-74.3068	-74.3532	-74.3659	-74.5154	-74.5307	-74.5457
Kilometre		40	55.5	57	65.5	90	95.5	96.5	110	111.5	112.5
Road name		A-15	R-117	A-15	R-117	R-117	R-117	R-117	R-117	R-117	R-117
AADT (2022)	Vehicules/ day	118,000	10,800	52,000	7,900	22,500	22,500	22,500	24,000	24,000	24,000
Type of structure		Bridge	Bridge	Culvert	Culvert	Culvert	Culvert	Culvert	Culvert	Culvert	Culvert
Number of structures		2	1	1	1	2	2	2	2	2	2
Construction year		1950, 2008	1942	1960	1962	1972	1972	1972	1958, 1970	1972	1978
Median size	m	25				13	30	6	22	24	27
Height	m	2.3	4.0	1.8	2.3	2.0	1.7	2.1	1.8	3.2	2.4
Width	m	60.6	68.7	3.7	4.6	14.4	14.6	7.8	3.0	5.9	6.1
Opening	m^2	139.4	274.8	6.5	10.6	28.8	24.1	16.3	5.4	18.9	14.6
Length by structure	m	19.2	13.9	58.3	33.4	16.0	12.8	12.8	31.9	32.9	33.8
Minimum water depth	cm	0	0	0	40	0	0	5	25	10	10
Distance to forest	m	9.5	8.25	17.5	10	10	12.9	16.45	9.75	1.75	7.15
Ecological corridor		No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
Natural area	%	26.7	41.3	58.1	59.8	71.4	89.2	82.4	42.8	71	60.3
Water body and wetland proportion	%	0.163	0.074	0.000	0.024	0.177	0.355	0.124	0.103	0.253	0.175
Road density	km/km^2	4.7	7.4	7	7.3	4.8	2.7	2.7	4.3	3.7	2.8
Camera days	Days	941	North: 1,645 South: 1,665	1,072	1,546	1,665	1,537	1,876	1,508	1,847	1,766

7.2.4 Diagram of the camera layout on a site, aerial view.

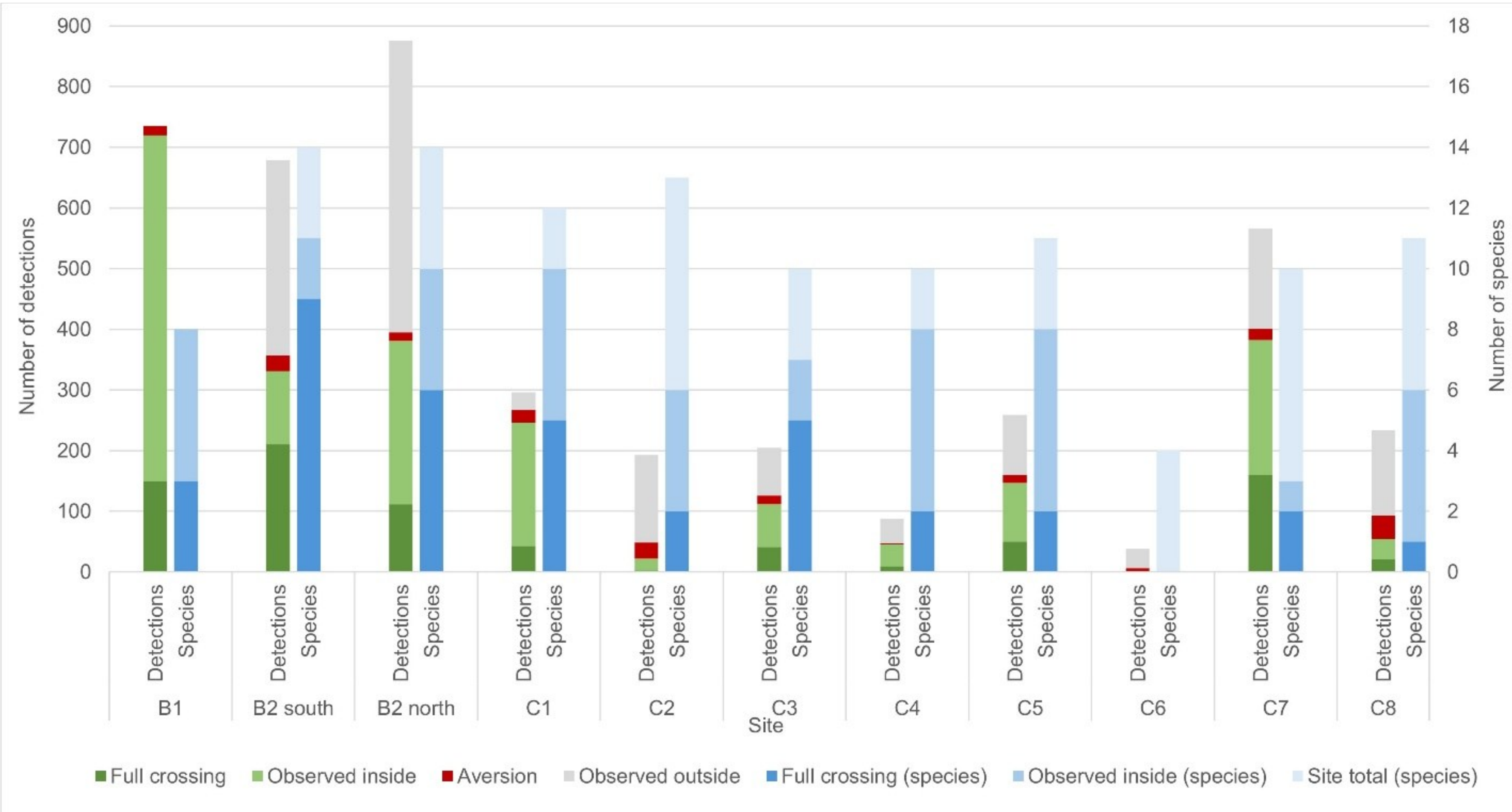


7.2.5 Photos of the animals at the sites. From top to bottom, left column: American mink, stoat or weasel, squirrel, raccoons. Right column: red fox, white-tailed deer, raccoons, beaver.

7.2.6 Number of detections by species or group of species, all sites combined, according to the type of detection.



7.2.7 Number of detections and number of species by site, according to the type of detection.



7.2.8 Number of detections by species, type of detection, and site.

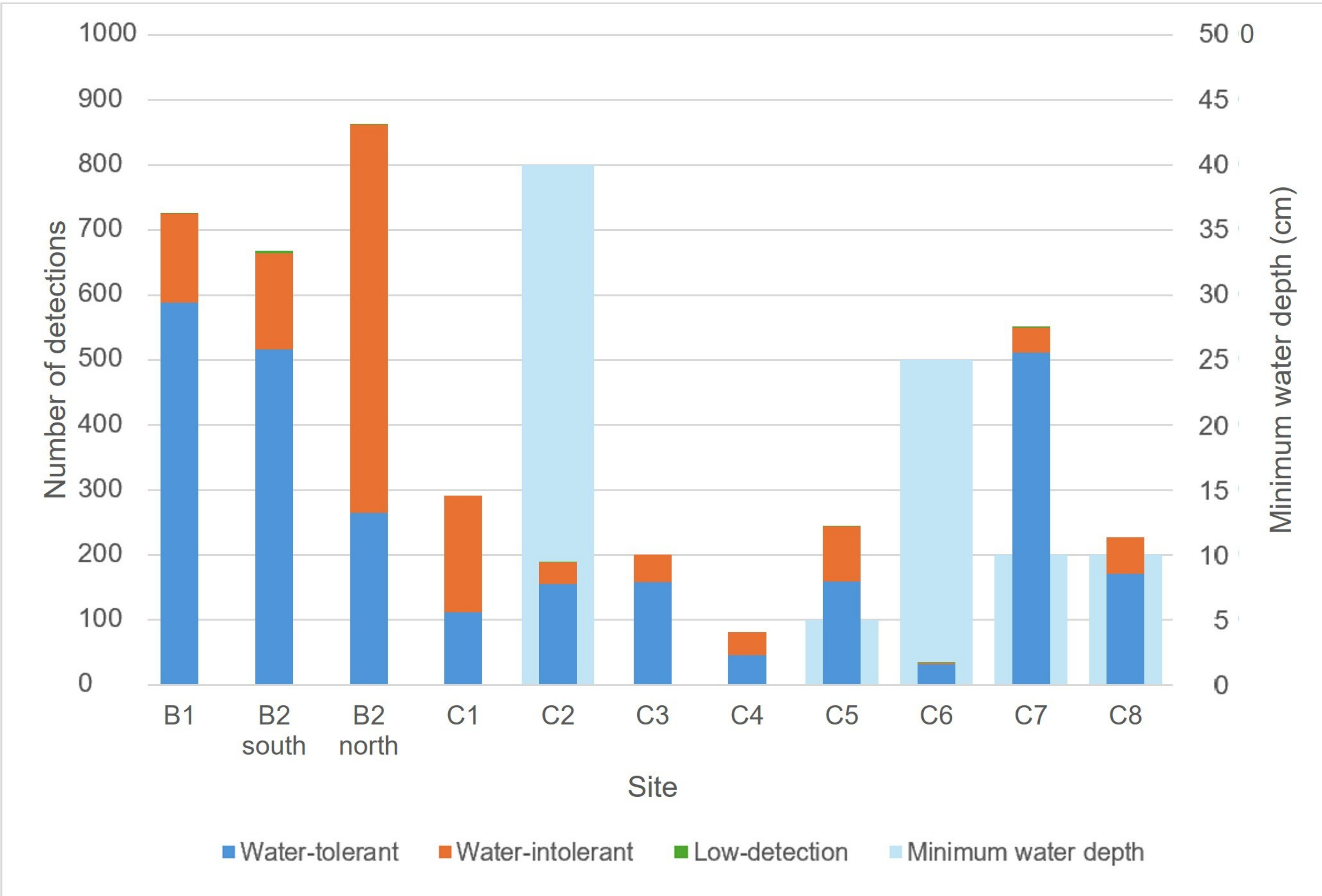
Species	Type of detection	B1	B2 south	B2 north	C1	C2	C3	C4	C5	C6	C7	C8	Total
American marten *Martes americana*	Full crossing												0
	Observed inside		1	1					1				3
	Aversion												0
	Observed outside												0
American mink *Neovison vison*	Full crossing		8								1		9
	Observed inside		5		14	1		5	22			1	48
	Aversion												0
	Observed outside		17	1	2	14	2	3	4		14	5	62
Beaver *Castor canadensis*	Full crossing												0
	Observed inside		1				2		2			1	6
	Aversion												0
	Observed outside			2		2		12	1			8	25
Brown rat Rattus norvegicus	Full crossing												0
	Observed inside												0
	Aversion												0
	Observed outside			1									1
Chipmunk *Tamias striatus*	Full crossing												0
	Observed inside			1	8				1				10
	Aversion					2							2
	Observed outside			1		2			2		1		6
Coyote *Canis latrans*	Full crossing												0
	Observed inside	1											1
	Aversion												0
	Observed outside												0
Domestic cat *Felis Catus*	Full crossing		1	20									21
	Observed inside			46		1							47
	Aversion			2									2
	Observed outside		1	66									67

Species	Type of detection	B1	B2 south	B2 north	C1	C2	C3	C4	C5	C6	C7	C8	Total
Domestic dog *Canis Familiaris*	Full crossing						1						1
	Observed inside			1			1						2
	Aversion										4		4
	Observed outside		1		1		1				2	3	8
Fisher *Pekania pennanti*	Full crossing		1										1
	Observed inside		1										1
	Aversion												0
	Observed outside		1										1
Groundhog *Marmota monax*	Full crossing	1	10	22	18		7	5					63
	Observed inside	73	24	36	37		12	12			3		197
	Aversion			6	6	4	1				8	20	45
	Observed outside		13	40	14	15	5	4	2		9	20	122
Hare *Lepus sp.*	Full crossing												0
	Observed inside	1			1								2
	Aversion							1	6				7
	Observed outside							6	26				32
Mouse or vole Undetermined species	Full crossing												0
	Observed inside		7		8			1	15				31
	Aversion					1							1
	Observed outside		16	11		1			22	2		1	53
Muskrat *Ondatra zibethicus*	Full crossing		2		1	1			1				5
	Observed inside		2	1	9	4	3	6	21				46
	Aversion												0
	Observed outside		6	9		41	1	5	18		2	37	119
Mustelidae	Full crossing												0
	Observed inside												0
	Aversion												0
	Observed outside				1				1		1	1	4

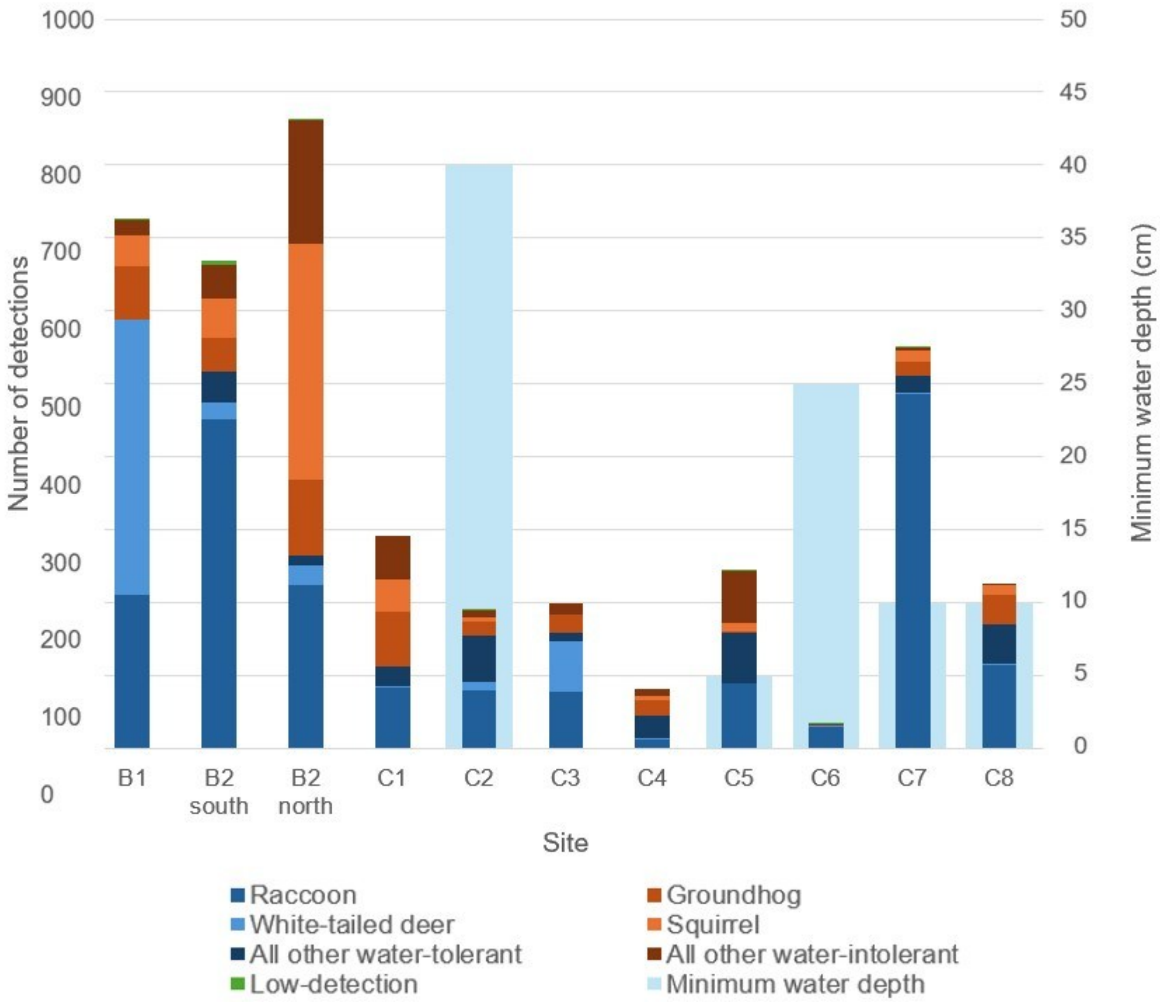
Species	Type of detection	B1	B2 south	B2 north	C1	C2	C3	C4	C5	C6	C7	C8	Total
Raccoon *Procyon lotor*	Full crossing	7	168	45	16		23	4	49		159	21	492
	Observed inside	197	59	59	57	2	10	4	25		209	27	649
	Aversion	6	17	4	11	20	1		7	4	5	15	90
	Observed outside		208	117		57	44	4	9	26	113	51	629
Red fox *Vulpes vulpes*	Full crossing		3	4			2						9
	Observed inside	20	1	7	3	1	3	1				1	37
	Aversion	1	5				2						8
	Observed outside		14	12			9						35
River otter *Lontra canadensis*	Full crossing												0
	Observed inside										2		2
	Aversion												0
	Observed outside					1				1			2
Squirrel *Sciurus sp.*	Full crossing		12	10	6								28
	Observed inside	41	13	106	31			3	4			2	200
	Aversion		2	2	3						1	2	10
	Observed outside		26	205	5	6	1	3	7		14	9	276
Stoat or weasel *Mustela sp.*	Full crossing				2								2
	Observed inside				32								32
	Aversion												0
	Observed outside				5	1					3	1	10
Striped skunk *Mephitis mephitis*	Full crossing												0
	Observed inside	4											4
	Aversion						1						1
	Observed outside		1				1		2				4
White-tailed deer *Odocoileus virginianus*	Full crossing	142	6	11		2	8						169
	Observed inside	228	2	9		10	39	2				1	291
	Aversion	8	2		1		9			2	1	1	24
	Observed outside		12	6		1	13				1		33

Species	Type of detection	B1	B2 south	B2 north	C1	C2	C3	C4	C5	C6	C7	C8	Total
Unknown species	Full crossing												0
	Observed inside	5	4	2	3		1	3	6		8	1	33
	Aversion												0
	Observed outside		6	10	1	3	2	4	5	3	5	5	44
Total	Full crossing	150	211	112	43	3	41	9	50	0	160	21	800
	Observed inside	570	120	269	203	19	71	37	97	0	222	34	16
	Aversion	15	26	14	21	27	14	1	13	6	19	38	194
	Observed outside	0	322	481	29	144	79	41	99	32	165	141	1,533
	Total	735	679	876	296	193	205	88	259	38	566	234	4,169
Number of species	Full crossing	3	9	6	5	2	5	2	2	0	2	1	11
	Observed inside	8	11	10	10	6	7	8	8	0	3	6	19
	Aversion	3	4	4	4	4	5	1	2	2	5	4	11
	Observed outside	0	12	12	5	11	9	7	10	3	9	9	18
	Total	8	14	14	12	13	10	10	11	4	10	11	20

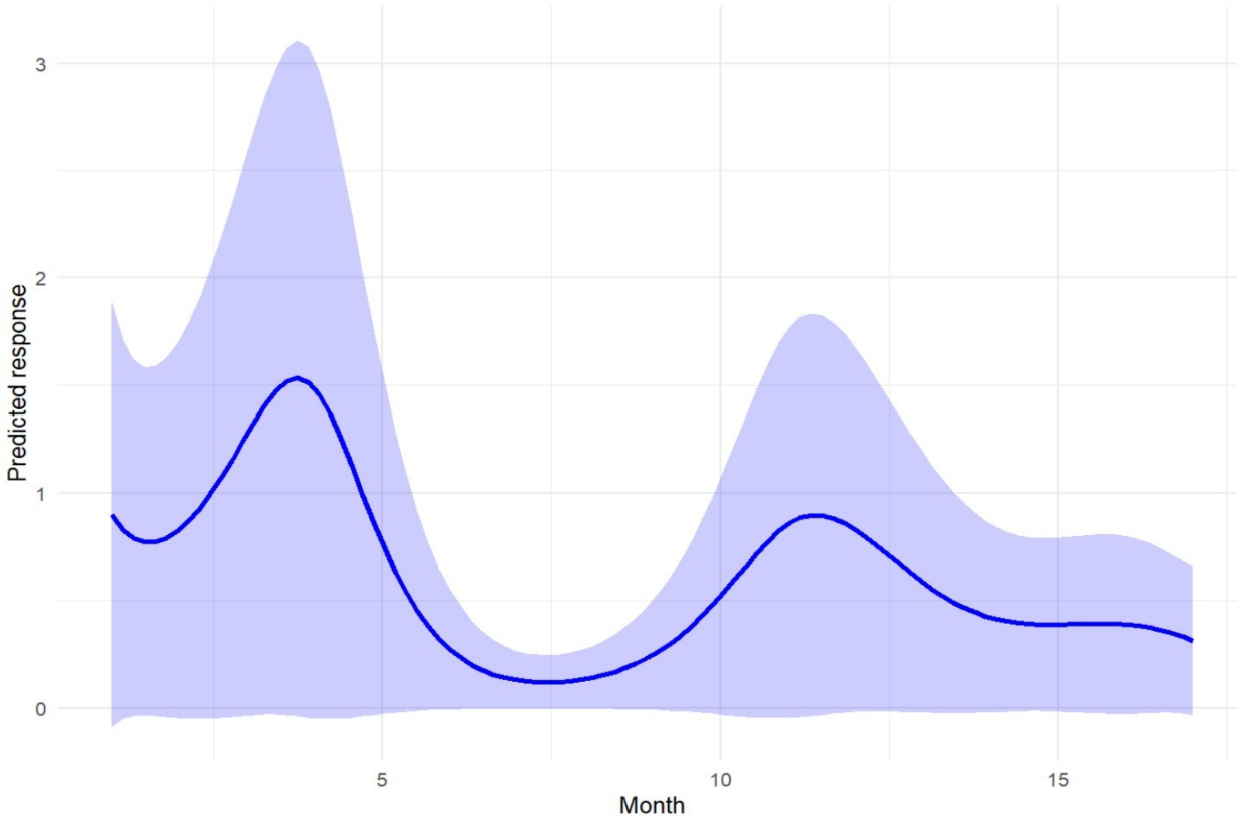
7.3 All detections by species group and minimum water depth to cross through per site.



7.4 All detections for four most often detected species overall and minimum water depth to cross through per site.



7.5 Predicted response of the spline by month for the global All-Species GLMM



7.6 GLMM(s) coefficients, variance, and significance as given by the summary function in R. Significance codes according to R: 0 < '*' < 0.001 < '**' < 0.01 < '*' < 0.05 < '.' < 0.1 < ' ' < 1.**

Type of GLMM(s)		GLMM(s)	Coefficient	Estimate	Std. Error	Adjusted SE	z value	Pr(>|z|)	Significance
Global GLMM		All-Species	Minimum water depth	-0.085814	0.029561		-2.903	0.003700	**
			Water body and wetland proportion	-5.027009	3.354352		-1.499	0.133960	
			Water coverage	0.185042	0.096850		1.911	0.056060	.
			Water flow average	0.020813	0.017035		1.222	0.221790	
			Opening	0.003345	0.003390		0.987	0.323790	
Averaged GLMMs	Group of species	All-Species	Minimum water depth	-0.077268	0.040125	0.040134	1.925	0.054194	.
			Water body and wetland proportion	-3.133242	3.843132	3.843875	0.815	0.415000	
			Water coverage	0.173064	0.119730	0.119756	1.445	0.148419	
			Water flow average	0.013816	0.018515	0.018519	0.746	0.455633	
			Opening	0.002346	0.003673	0.003674	0.639	0.523053	
		All-Species weights 1	Minimum water depth	-0.059879	0.036262	0.036269	1.651	0.098750	.
			Water body and wetland proportion	-2.484449	3.307940	3.308574	0.751	0.452710	
			Water coverage	0.200440	0.106362	0.106389	1.884	0.059560	.
			Water flow average	0.009730	0.015250	0.015253	0.638	0.523550	
			Opening	0.003078	0.003673	0.003674	0.838	0.402130	
		Water-tolerant	Minimum water depth	-0.030706	0.034082	0.034098	0.901	0.367850	
			Water body and wetland proportion	-0.077250	2.044141	2.046143	0.038	0.969884	
			Water coverage	0.047884	0.097873	0.097934	0.489	0.624883	
			Water flow average	0.077166	0.021102	0.021123	3.653	0.000259	***
			Opening	0.001158	0.002727	0.002729	0.424	0.671214	
		Water-intolerant	Minimum water depth	-0.082458	0.039940	0.039954	2.064	0.039040	*
			Water body and wetland proportion	-6.714336	4.541594	4.543036	1.478	0.139420	
			Water coverage	0.026892	0.084552	0.084603	0.318	0.750590	
			Water flow average	-0.003084	0.014495	0.014505	0.213	0.831610	
			Opening	0.002692	0.003945	0.003946	0.682	0.495090	

Type of GLMM(s)		GLMM(s)	Coefficient	Estimate	Std. Error	Adjusted SE	z value	Pr(>|z|)	Significance
Averaged GLMMs	Individual species	Raccoon	Minimum water depth	-0.021526	0.030037	0.030118	0.715	0.474784	
			Water body and wetland proportion	-0.691832	2.285389	2.295439	0.301	0.763114	
			Water coverage	0.015485	0.067994	0.068376	0.226	0.820840	
			Water flow average	0.003621	0.011556	0.011617	0.312	0.755280	
			Opening	0.004870	0.004146	0.004158	1.171	0.241415	
		White-tailed deer	Minimum water depth	-0.000320	0.052072	0.052353	0.006	0.995120	
			Water body and wetland proportion	2.109778	7.298190	7.334315	0.288	0.773608	
			Water coverage	-0.027344	0.133852	0.134662	0.203	0.839089	
			Water flow average	-0.004952	0.022891	0.023029	0.215	0.829757	
			Opening	0.013942	0.012384	0.012422	1.122	0.261726	
		Squirrel	Minimum water depth	-0.028533	0.041337	0.041446	0.688	0.491171	
			Water body and wetland proportion	-2.224293	3.902291	3.913822	0.568	0.569820	
			Water coverage	0.010832	0.117020	0.117638	0.092	0.926633	
			Water flow average	-0.019998	0.034430	0.034551	0.579	0.562725	
			Opening	0.013239	0.005305	0.005324	2.487	0.012897	*
		Groundhog	Minimum water depth	-0.033773	0.044503	0.044627	0.757	0.449190	
			Water body and wetland proportion	-0.816348	3.003214	3.017582	0.271	0.786750	
			Water coverage	-0.045817	0.126167	0.126750	0.361	0.717750	
			Water flow average	-0.005137	0.019045	0.019149	0.268	0.788500	
			Opening	0.004763	0.005356	0.005371	0.887	0.375150	
	Track paper species	With track papers by month	Minimum water depth	-0.142582	0.046756	0.046784	3.048	0.002306	**
			Water body and wetland proportion	-0.390357	2.031833	2.033595	0.192	0.847778	
			Water coverage	0.145839	0.134959	0.135024	1.080	0.280097	
			Water flow average	-0.002319	0.012427	0.012436	0.187	0.852043	
			Opening	0.004013	0.003191	0.003193	1.257	0.208732	
			Track paper	0.128843	0.032079	0.032111	4.012	0.000060	***
		With track papers by two-week period	Minimum water depth	-0.131302	0.065671	0.065738	1.997	0.045790	*
			Water body and wetland proportion	0.243943	2.066590	2.070253	0.118	0.906200	
			Water coverage	-0.024149	0.248233	0.248544	0.097	0.922600	
			Water flow average	-0.012308	0.042039	0.042104	0.292	0.770030	
			Opening	0.004744	0.003553	0.003556	1.334	0.182240	
			Track paper	0.587793	0.142198	0.142471	4.126	0.000037	***

Type of GLMM(s)		GLMM(s)	Coefficient	Estimate	Std. Error	Adjusted SE	z value	Pr(>|z|)	Significance
Interaction GLMMs	Main effects only GLMM		Minimum water depth	-0.085934	0.029526		-2.910	0.003610	**
			Water body and wetland proportion	-5.051899	3.349871		-1.508	0.131530	
			Water coverage	0.184512	0.096850		1.905	0.056760	.
			Water flow average	0.020433	0.017036		1.199	0.230390	
			Opening	0.003360	0.003385		0.992	0.320990	
			Water tolerance	0.960894	0.807479		1.190	0.234050	
	Main and interaction effects GLMM	Main effects	Minimum water depth	-0.113237	0.031692		-3.573	0.000353	***
			Water body and wetland proportion	-7.971180	3.482119		-2.289	0.022069	*
			Water coverage	0.215862	0.117054		1.844	0.065164	.
			Water flow average	-0.033786	0.024335		-1.388	0.165019	
			Opening	0.004133	0.003520		1.174	0.240338	
			Water tolerance	-0.885894	1.012287		-0.875	0.381497	
		Interaction effects	Minimum water depth	0.055338	0.019401		2.852	0.004340	**
			Water body and wetland proportion	7.514892	1.626851		4.619	0.000004	***
			Water coverage	-0.054147	0.148747		-0.364	0.715846	
			Water flow average	0.104845	0.032550		3.221	0.001277	**
			Opening	-0.001609	0.001582		-1.017	0.309123	