How do ambient and structural variables influence the entry into and full passage of drainage culverts by mammals and their ability to act as wildlife passages?

Benjamin Brunen

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ABSTRACT

Roads present a significant barrier to wildlife movement for many species. While designated wildlife crossing structures have been heralded as an attractive solution to many of the problems associated with roads, they are often prohibitively expensive. Autoroute 10 in Southern Quebec is one of many highways in Canada that would benefit from such structures, but currently has none in place. However, the highway has a series of periodically placed drainage culverts designed to allow water to cross underneath the road surface. Through monitoring trail camera footage inside of 13 drainage culverts, and animal track stations along a 20 kilometre stretch of highway A10, this project aims to (1) determine what factors influence the number of full passages of drainage culverts by mammals, and (2) parse the effects that these factors have on the entry into and subsequent full passage of drainage culverts by individual animals. Overall, 20 species were observed outside of the drainage culverts in this study, but only animals highly tolerant to water, including raccoons and American mink, were observed fully crossing the structures with regularity. Water level and polyethylene as a construction material were the strongest deterrents for both the number of full passages, as well as entry into the culverts. Additionally, we found that many factors influenced an individual entering a culvert, while no variables impacted its full passage once it had entered.

Moving forward, this data will be invaluable in determining where best to focus future habitat fragmentation mitigation efforts along highway 10. In this study we introduced zero-inflated negative binomial generalized linear mixed models as a statistical method in a road ecology study for analyzing the effects that variables have on excess zeros in the data, as well as the value of combining trail camera data inside of drainage culverts with track data in the adjacent habitat. We conclude that drainage culverts are ultimately not suitable substitutes for designated crossing structures for mammals, and recommend that where it is not feasible to install designated wildlife crossing structures, dry ledges be installed in existing drainage culverts to better allow small- and medium-sized mammals to safely cross under the road surface while avoiding the water inside of them. Future road ecology studies are needed along all major

highways, both with and without mitigation measures already in place, to better understand the effects that roads are having on wildlife.

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Contribution of Authors

As first author, I was responsible for the conception, design, data analysis and the writing of the manuscript related to this thesis. The manuscript was co-authored by Caroline Daguet, who assisted with obtaining the necessary government permits to conduct this study, and Dr. Jochen Jaeger, who advised on experimental design, statistics, editing, and overall revisions to the manuscript.

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In loving memory of my father, Thomas Brunen

INTRODUCTION

Roads, while in many ways vital to humankind, act as drivers of contagious development (Ibisch et al. 2016); where roads are constructed, additional development tends to follow closely behind. Many mammalian species are negatively impacted by roads through animal-vehicle collisions, decreased habitat quality, and the ecological effects associated with habitat patch edges made by the road, effectively reducing the sizes of the remaining patches (Jaeger 2012). Together, these factors reduce animal willingness to cross or travel near the road surface, making it a barrier to their movement (McGregor et al. 2008). When this barrier effect is severe, the rate of successful crossings can be reduced to such a point that populations may become genetically isolated due to too few individual transfers between populations (Stacy & Taper 1992). This effect has been documented, and can result in the local extinction of vulnerable species (Ascensão et al. 2016).

Ecological corridors, or linear landscape elements that connect two or more patches of habitat, are critical components in an increasingly fragmented world (Soule & Gilpin 1991). Animals that may have otherwise been restricted to one isolated patch of habitat are able to move through ecological corridors, extending their home range and increasing genetic diversity within populations (Lindenmayer & Nix 1993). However, roads often cut through ecologically significant areas including ecological corridors, disrupting the movement and migration of animals using them (Havlick 2004). In the southern Quebec Appalachian mountain range, autoroute 10, a four-lane provincial highway providing access to motorists from Montreal to Sherbrooke, bisects nine proposed naturally established ecological corridors in some places connecting habitat within a national park, Parc national du Mont-Orford, to forested habitat on the south side of the highway.

While there are no designated wildlife passages along Quebec's autoroute 10, drainage culverts, structures placed underneath the road surface to allow water drainage from one side of the road to the other, are placed at regular intervals. Many studies have shown the potential of drainage culverts to act as non-designated crossing structures for small- to medium-sized mammals (Yanes et al. 1995; Rodriguez et al. 1996; Marangelo & Farrel 2016), indicating that movement within the bisected ecological corridors may not be entirely cut off for animals that use these structures. As Quebec's ministère des Transports plans to replace several damaged and aged drainage culverts under autoroute 10, a rare opportunity has presented itself where site-specific data may be used to inform decision makers on how best to incorporate the facilitation of animal movement in otherwise purely drainage-focused structures.

Analyzing the activity of mammals in and around drainage culverts under autoroute 10 will help determine the most effective crossing type to assist animals in travelling from one side of the road to the other. As various studies document that characteristics both of the drainage culvert itself and the area surrounding it impact which species are likely to use the structure, this study will determine effectiveness based on criteria established in the literature (Clevenger et al. 2001; Ascensão & Mira 2007; Mata et al. 2008). Using these data, recommendations can be made to inform decision makers on what drainage culvert type will best serve the passage of wildlife while still maintaining its original function.

LITERATURE REVIEW

The problem with roads

Habitat Fragmentation

Habitat fragmentation is a term describing the abrupt discontinuation of same or similar environment types into smaller patches (Franklin et al. 2002). It can be observed naturally in landscapes bisected by rivers or made temporarily inhospitable by fires, although anthropogenic habitat fragmentation occurs at a much higher intensity and impacts landscapes much more severely. Fragmentation as a process involves four main effects on habitat: reduction in habitat amount; increase in number of habitat patches; decrease in size of habitat patches, and increase in the isolation of habitat patches (Fahrig 2003; 2017). One of the leading drivers of anthropogenic habitat fragmentation is the ever-expanding road network connecting human settlements.

While a serious problem in itself, the effects of habitat fragmentation are often confused with habitat *loss* as a result of fragmentation. Coined habitat fragmentation *per se*, this distinction of effects recognizes that the actual fragmentation of habitat often has very minor ecological impacts compared to the habitat loss resulting from fragmentation (Fahrig 2003). For example, dividing a landscape in two in and of itself may cause some animals to not be able to access areas of their former home range, but the degradation of the habitat in proximity to the new habitat edge as a result of the edge effect will have far greater ecological repercussions.

For example, Sizer and Tanner (1999), in a study analyzing pioneer tree seedlings in an ecosystem before and after fragmentation, found that the direct solar radiation penetrating from the newly introduced habitat edge resulted in pioneer tree species only being present at a minimum of 10 meters into the forest. Furthermore, in a similar study, Laurance (1991) observed marked increases in forest damage up to 200 meters from edges resulting from habitat fragmentation. Because of the negative effects associated with, but not necessarily caused directly by habitat fragmentation, specialist species living within non-affected habitat will likely avoid edge habitat because of its unsuitability. It is through these processes that animal movement can decline to such an extent that inter-population breeding comes to a halt altogether, leading to genetic isolation and eventually local extinction (Rodriguez et al. 1996).

Road Ecology

Where roads exist, wildlife habitats are degraded (Forman et al. 2003). Fragmentation decreases habitat size and quality, while vehicles travelling on the road discourage or prevent animals from crossing. While the habitat lost to the construction of roads is relatively small (usually around one to two percent of a given country's land), the ecological effects of roads have been measured to affect up to 20% of the land in the United States (Forman 1998; 2005). These impacts have increased over time as road networks have expanded (Roedenbeck et al. 2007). Similarly, 50% of land in Europe is located within 1.5 kilometres of roads (Torres et al. 2016). Roads affect ecosystems to such an extent that evolutionary changes across species have been observed, with road-adjacent populations differentiating from nearby populations in their capacity to tolerate road effects (Brady & Richardson 2017). This leads to an increased abundance of generalist species in road-affected areas, driving out more highly specialized (and often more at-risk) species (Pocock & Lawrence 2005).

Although positive and neutral effects of roads exist for some species, 59% of studies analyzing the effects of roads have found negative effects on animal populations (Downing et al. 2015). Through traffic mortality, population subdivision, resource inaccessibility, noise and light emissions, air pollution, and chemical runoff (Jaeger et al. 2005), roads act as linear barriers effectively fragmenting the landscape in which they are situated into smaller parcels. For many species these barriers are impenetrable (Ascensão et al. 2016). When animals are unable to cross roads, their home ranges can be severely reduced, often resulting in islands of populations where inter-population movement (Ascensão et al. 2016) and recolonization of uninhabited habitat patches (McGregor et al. 2008) is highly restricted.

Positive effects are most often associated with species that are drawn to areas with roads because of the presence of a resource (for example roadkill), but have the cognitive ability to avoid oncoming traffic (Fahrig & Rytwinski 2009). Crows and vultures are examples of this phenomenon. Another positive effect of roads has been hypothesized as the predation-release hypothesis, whereby prey species may increase in abundance as a result of their predators being killed by vehicles on the road surface (Rytwinski & Fahrig 2013). However, no evidence was found to support this theory (Downing et al. 2015). Similarly, neutral effects can be observed for species including mice and voles that live in small home ranges and have a high reproductive rate, making nearby roads largely irrelevant as their life cycles do not require travelling far enough to require having to pass over the road surface, or even travel near it (Fahrig & Rytwinski 2009).

Mitigating the negative effects of roads

Road Mortality

Wildlife mortality on roads, while preventable, is largely ubiquitous around the world. To better understand how animal populations are affected by vehicle collisions, documenting and analyzing the pattern and frequency of these collisions have become invaluable tools (Rytwinski et al. 2016; Heigl et al. 2017). Studying wildlife mortality on roads can give researchers a detailed look into which species are impacted, and to what extent. This information can then be compiled to identify roadkill hotspots, which can be used to determine the best locations for road mitigation measures to reduce animal mortality on roads. Over 40 such mitigation measures have been implemented and tested in studies, and can typically be divided into two categories: those that influence motorist behavior, and those that influence animal behavior (Hedlund et al. 2004).

Motorist behavior can either be altered in such ways that awareness of the possible presence of animals is increased, or motorist speed is reduced to an extent that if an animal were to appear on the road, there would be enough time to react safely. Motorist awareness measures often include general education programs, where either through ads or campaigns motorists are made aware of the dangers posed by wildlife-vehicle collisions (WVCs). Additionally, on-the-road awareness measures including “caution: deer” signs and lighted warning signs are often implemented (Hedlund et al. 2004). While these measures are very common in many areas around the world, their effectiveness has been challenged and in many cases disproven due to motorist habituation (Reed et al. 1975; Åberg 1981). Reducing posted speed limits on roads has been shown to reduce WVCs, but only if the road is actively patrolled by law enforcement (Lavsund and Sandegren 1991; Hedlund et al. 2004).

Animal behavior near roads can be altered to either reduce animal presence around the road surface, or encourage animals to cross roads at designated locations. Experimental measures to increase road avoidance have largely revolved around ideas of using light and noise to scare animals away from the road surface, although most studies testing these measures have shown that they are ineffective

(Ujvari et al. 1998; Romin & Dalton 1992). An evident gap in the literature in this area includes analyzing the correlation between wildlife mortality hot spots and their proximity to wildlife corridors.

Ecological Corridors

Fifty to seventy percent of the earth's land surface has been modified due to human activities (Barnosky et al. 2012). Because of this large-scale land modification, natural habitats are becoming increasingly small and isolated, causing observable reductions in mammal movement across the globe (Tucker et al. 2018). These reductions in mammalian vagility, or ability for animals to move over large distances, make it more important than ever to maintain individual exchange between habitat patches to contribute to the long-term survival of sub-populations living in relatively isolated areas (Gilbert et al. 1998; Kramer-Schadt et al. 2004). Increasingly, networks of wildlife corridors are being advocated as a potential solution to the problem of maintaining connectivity in fragmented landscapes (Saunders & Hobbs 1991).

Corridors, usually linear in shape, are bands of habitat connecting two or more patches of similar habitat in a matrix, allowing for organisms to move among them (Hilty et al. 2006). The perceived importance of corridors in ecology stems from island biogeography, in particular the idea that if left isolated, an island will experience a higher extinction rate than islands with some degree of connectivity between them (Simberloff & Abele 1976). Similarly, terrestrial "islands", or habitat patches, have been observed to experience a higher extinction rate if completely isolated compared to patches with corridors linking them to other patches. However, this is largely theoretical, as terrestrial habitat patches are very rarely completely isolated, and several positive effects have been observed resulting from habitat fragmentation (Fahrig 2003, 2017). The importance of intact ecological corridors, despite this, is very important for the movement of wildlife. For example, a study analyzing the effects of fragmentation on a micro ecosystem found that corridors linking habitat patches reduced species loss by 25.5% (Gilbert et al. 1998). The same study, however, found that patches connected to broken corridors showed the same results as those without any corridor. Therefore, the need to preserve and in many cases create new wildlife corridors is paramount in order to maintain connectivity between patches in landscapes where human development is constantly expanding.

How best to manage or plan for the most effective corridor design is a topic of contention, with some advocating the facilitation of passage for individual species, as was the case in Florida for panthers (Cramer & Portier 2001), and others calling for community-focused corridors such as the large-scale Yellowstone-to-Yukon ecoregion (Walker & Craighead 1998). The best approach is often determined on a case-by-case basis, with the presence of critically endangered species likely playing a strong role in decision making. Generally, however, connectivity planning for entire communities is seen as the catch-all solution, because community integrity affects individual species' persistence (Hilty et al. 2006).

Wildlife Passages

One way of alleviating some of the negative effects of roads is to build wildlife passages over or under the road surface. These bridges or tunnels act as micro-corridors for animals to safely cross to the other side of a road without having to interact with the road surface or the vehicles travelling on it. Wildlife passages are often supported as objects both facilitating connection between habitats separated by roads, and improving motorist safety by reducing WVCs (Clevenger & Huijser 2009). First implemented in 1950 in the form of box culverts to allow black bears to cross under a highway in Florida, wildlife crossings are a relatively recent addition to road networks given the centuries-long history of roads (Cramer & Bissonette 2005). Recently in North America, there have been nearly 500 designated wildlife crossings installed for mammals and over 300 for aquatic species (Cramer & Bissonette 2005).

There are two categories of wildlife passages: underpasses and overpasses. Underpasses allow animals to travel underneath the road surface, and can take shape either as tunnels under the road, or as flyovers, where pillars elevate the road surface over a dip in the landscape. Larger mammals typically prefer more open spaces, opting to use fly-overs more than smaller mammals who tend to prefer smaller spaces such as drainage culverts or smaller underpasses (Beben 2012). Wildlife overpasses, those passages that act as "green bridges" or ecoducts crossing over a road surface, are advocated by ecologists and the public alike for providing ecological (and attractive looking) links across busy highways (Glista et al. 2009).

Some species have been found to use certain passage types over others. For example, smaller mammals are often observed crossing smaller passages more than larger ones (Niemi et al. 2014), while passages with greater openness ratios (structure *width* x *height* / *length*) tend to be used by larger mammals including bear, wolf, elk, and deer (Glista et al. 2009). Additionally, smaller species have been observed using structures with heavy vegetation cover near structure entrances more than those lacking it (McDonald & St Clair 2004), and structures with a soil substrate at the structure bottom have been shown to be visited more by all species compared to structures without (Reed et al. 1975; Glista et al. 2009).

Drainage Culverts

Emerging research has found that in addition to wildlife over- and underpasses, structures not originally designed to facilitate animal movement may be playing a vital role in allowing animals to cross under roads in areas without any designated wildlife crossing structures (Clevenger & Barrueto 2014). Perhaps the most common of these non-wildlife passages is the drainage culvert. Varying in material and structure, drainage culverts are designed to allow water to pass freely under roads. Drainage culverts are typically 0.5 to 2.0 meters in diameter and span the entire width of a road. In addition, they often create a suitable corridor for reptiles and amphibians (Glista et al. 2009), small mammals (Beben 2012), and medium sized mammals (Mata et al. 2008) to safely cross a road without having to use the road surface itself. This is true particularly when water levels are low.

Indeed, research has found that drainage culverts assist many species in crossing roads (McDonald & St Clair 2004), with one study finding a 93.5% reduction in traffic-related animal mortality through the implementation of culverts and exclusion fencing (Glista et al. 2009). Further research into the effectiveness of drainage culverts as wildlife passages is paramount in part due to the minimal cost of maintaining or adapting already existing structures to serve both hydrological and ecological needs (Mata et al. 2008).

Both types of crossing structures, those designed for wildlife and those that "accidentally" serve as crossings such as drainage culverts, have specific characteristics that attract different species. Determining which attributes encourage certain species to utilize them over other designs has been a focus of several studies (Reed et al. 1975; Clevenger & Waltho 2000). Generally, these attributes can be classified into four categories: structural (Mata et al. 2008), landscape (McDonald & St Clair 2004), animal behaviour (Ng et al. 2004), and geographical (Bissonette & Adair 2008). Knowing which characteristics a given species is most affected by can be highly useful in management planning, particularly if the species is at risk.

The structural variables of crossing structures likely play a major role in influencing visits to a crossing (Krawchuk et al. 2005). These dimensions include a crossing's width (w), height (h), length (l), and openness ratio ($O = ((h \times w) / l)$). For example, crossing structures with greater openness ratios have been shown to be better suited for large mammals (Glista et al. 2009), while smaller mammals including weasels have been found to prefer crossings with lower openness ratios (Clevenger et al. 2001). This demonstrates the need for varying sizes of crossings along a given highway to better serve all species.

Landscape components in the surrounding environment around a crossing structure include vegetation at crossing openings, type of surrounding forest cover (e.g. coniferous or deciduous stands, stand age), noise levels, or exclusion fencing bordering a road. These components are often difficult to incorporate into the planning of a crossing structure project, as noise levels may change depending on the time of year, and vegetation can take time to mature, often changing seasonally. Vegetation has been shown to be a highly important factor in the use of wildlife crossings, particularly for small mammals (McDonald & St Clair 2004; Glista et al. 2009), with some species exclusively visiting crossings with vegetation near the crossing's opening, while others prefer no vegetation (Ascensão & Mira 2007).

Geographical location of crossing structures may seem like a less important aspect when determining structure effectiveness, but in reality location is paramount to many species (Glista et al. 2009). Placing a wildlife crossing with fencing at a point of high animal-vehicle collisions has been shown to drastically reduce the frequency of animal mortality on the road surface, having significant beneficial effects on both the animal populations and motorists using the road (Bissonette & Adair 2008). Additionally, strategically placing crossing structures in line with wildlife corridors can help aid animal movement, effectively forming a bridge between segments of linear habitat (Clevenger & Huijser 2009). Recent studies have placed emphasis on the role of wildlife corridors (Kramer-Schadt et al. 2004; Pino & Marull 2012), bringing forward the insight that simply facilitating movement of animals from one side of a road to the other may not be sufficient if there is no suitable habitat on the other side.

Animal behaviour in and around drainage culverts can have important implications for the effectiveness of such structures. For example, when entering a drainage culvert, an animal can either directly cross from one end to the other, or explore parts of the structure and exit the same entrance from which it entered (Ng et al. 2004). While this behaviour is common for animals exploring a new object, persistent "explorations" rather than complete "passages" may indicate that some aspect of the structure is not suitable for the animals for full crossings.

Measuring animal activity around roads

Animal road mortality surveys

Animal mortality through WVCs has a major negative effect on population size for many species (Green 1991). Generally, animals are most often struck by vehicles where roads are surrounded by forested areas, relatively low crop cover, and low presence of human settlements (Malo et al. 2004). Simply put, clusters of road mortality are influenced where human highways cross animal highways (Havlick 2004).

There is strong evidence that with expanding road networks and shrinking habitat sizes, road mortality is increasing over time (Hedlund et al. 2004). Males across species are killed more often than females on roads, largely because of males' larger range sizes necessary for finding mates outside of their family groups (Heggeberget 1991). Given that actual levels of road mortality are estimated to be many times higher than directly observed mortality figures (Philcox et al. 1999), consistent, reliable road mortality data are essential to develop effective mitigation plans to reduce mortality on roads. This is accomplished with road mortality surveys that identify the species and locations of roadkill on a given stretch of highway.

Road mortality surveys typically take place daily, as animal carcasses do not remain on the road surface for very long, either due to carrion scavengers or highway authorities (Heigl et al. 2017). In a meta-analysis reviewing 1450 journal articles containing the phrase “vertebrate roadkill survey”, Collinson et al. (2014) found that a rough consensus exists that the optimal speed of the mortality surveyor along the highway is 50 km/hour, that the surveyor should always be the same person throughout the study, and that 65 observation days are usually sufficient to obtain a strong sample of road mortality. The time of day that the survey takes place has been shown to have effects on the number of roadkill identified per day, with more instances of road mortality identified in the mornings compared to evening surveys for small mammals, and the opposite for medium-sized mammals (Plante et al. 2019).

Reducing animal mortality on roads can be accomplished in three general ways: my modifying the behaviour of motorists; by modifying the behaviour of animals; or by reducing the number of animals in a given area (Hedlund et al. 2004). The latter option is typically reserved for problematically populous species such as deer or invasive species that present an ecological threat if kept unchecked. While effective mitigation measures have been identified, implementation should still be on a case-by-case basis, and more road mortality studies are needed. Few studies have analyzed the effects of road mortality on small mammals (Plante et al. 2019), in particular in Canada. Additionally, there is a need for more before-after-control-impact studies analyzing the effects of wildlife fencing on road mortality (Rytwinski et al. 2016).

Track box surveys

To determine if the species interacting with roads (either through visiting crossing structures or through road mortality) are representative of the community within the adjacent forest, it is necessary to compare samples from each group. Non-invasive survey methods are the standard tool used to estimate the presence, abundance, and/or density of species in a given area, as no harm is done to the animals, and the bias of human presence is largely avoided. In particular, tracking stations, also called track boxes or track plates, have been widely used to determine which species are present in a given area, with its first documented use by Cook (1949). Track boxes can be used to provide an index of abundance by calculating the percentage of boxes visited by a given species, but are most often used to determine presence-absence among species (Drennan et al. 1998).

Tracking stations implement either biodegradable ink or soot to imprint an animal's paw prints onto a surface that researchers later remove from the study area to inspect (Barrett 1983), and are often baited with poultry, fish, or a scent lure to attract more animals (Ray & Zielinski 2008). Lures are typically made of mixtures of animal oils, with mink and salmon being commonly implemented (Loukmas et al. 2003). Track boxes are often lightweight, portable, and durable, making them ideal for the occasionally harsh and constantly changing conditions in many forest environments (Ray & Zielinski 2008).

Track boxes have their strengths and weaknesses. Benefits of using track boxes include their affordability, the relatively low amount of training required to collect the data, and minimal site preparation during installation (Ray & Zielinski 2008). However, compared to other survey methods including trail camera surveys, they are much more labour intensive, require training to correctly identify animal tracks, are more vulnerable to water damage, and give less detailed data, making it sometimes difficult to draw confident conclusions from them (Whisson et al. 2005).

Track boxes have been used to determine the presence of small to medium sized mammals in riparian areas (Loukmas et al. 2003), of lynx, wolverines, fishers, and martens in forest ecosystems (Zielinski & Kucera 1995), and the relative abundance of rodent populations (Whisson et al. 2005), among others. Given the broad spectrum of survey designs and target species used in experiments, track boxes can be highly valuable tools for estimating presence-absence and abundance of species if used correctly. Very few studies exist that use track boxes to determine a crossing structure's performance index, calculated by comparing the number of species outside of a crossing structure to those that visit the structure itself (Bélanger-Smith 2014).

Trail Camera Surveys

There has been a significant increase over the past ten years in publications involving the use of camera traps, or trail cameras, to detect the movement of animals (Rowcliffe et al 2008). Camera trapping is a non-invasive wildlife survey method using remotely triggered cameras that take the image of animals or other subjects passing in front of them (Rovero et al. 2013). This is typically accomplished by connecting a camera to an instrument that projects an infrared beam that triggers the camera shutter when the beam is interrupted by objects moving past it (Rovero et al. 2013). Today, trail cameras use passive infrared sensors that detect changes in heat and motion compared to the background landscape (Reconyx 2013). When a change is detected, the built-in digital camera takes bursts of images of the subject moving past the camera.

The first documented instance of wildlife photography was in 1863, not long after the invention of the camera itself, in South Africa by the German explorer and Professor G. Fritsch (Guggisberg 1977). Following shortly behind this achievement was photography's inception into the scientific community, with cameras being deployed with the ship HMS Challenger in 1872 to photograph rookeries of penguins and breeding albatrosses (Kucera & Barrett 2011). Soon, however, the desire to observe animals in their natural habitat without the bias of human presence led to the introduction of trigger-cameras, where a string or tripwire, when pulled by the animal, triggered the camera shutter (Kucera & Barrett 2011). Today, trail cameras are compact, high quality, and relatively affordable, allowing for studies that increase our understanding of animal populations and their movements within their habitats.

Most often, camera trapping in research projects is used to conduct faunal checklists, to detect endangered species, for abundance estimations, occupancy estimations, or monitoring of wildlife crossings (Rovero et al. 2013). In a meta-analysis of camera-trapping studies, Burton et al. (2015) found that mammals were the focus of 94.8% of all published studies involving camera traps, and that the two main objectives of studies were measuring relative abundance of species (43.6%) and presence-absence of species (41.4%). Determining presence-absence as well as the number of visits to wildlife crossings has been of interest in many publications. For example, Ng et al. (2004) used cameras to determine which animals used wildlife underpasses to calculate crossing effectiveness, and Marangelo and Farrell (2016) used cameras for the Nature Conservancy to determine animal activity in wildlife passages and drainage culverts to find the best areas for upgrading crossing structures.

While some studies exist concerning the measurement of animal use of drainage culverts as crossing structures (Rodriguez et al. 1996; LaPoint et al. 2003; Krawchuk et al. 2005), very few studies have been conducted in Canada and specifically Quebec. Trail cameras present an exciting opportunity to monitor animal activity non-invasively, and to a large extent without the bias of human presence. This allows for the collection of high-quality data, giving researchers a valuable look into the movement of animals within and between populations.

Explanatory variables

To evaluate the relationship that animals have with roads and the structures underneath them (including drainage culverts), studies employ a variety of explanatory variables in an attempt to explain why animals behave the way they do. For example, when exploring what factors might affect wildlife use of drainage culverts, studies have used variables typically grouped into two categories: variables describing the culvert's physical characteristics, and variables describing the surrounding environmental characteristics.

Structural characteristics of crossing structures most often include very basic variables including the structure's length, width, and height (Grilo et al. 2008; Mata et al. 2008). For example, Krawchuk et al. (2005) observed that mule deer (*Odocoileus hemionus*) used structures of a lower openness ratio than previously thought. Additionally, Seiler et al. (2003) found that drainage culverts with smaller dimensions received fewer visits than similar studies that observed larger structures. Structural variables often branch out to the type of structure being studied; for example studies that compare the performance of drainage culverts to designated wildlife underpasses (Grilo et al. 2008). It is strange, however, that structure material, for example concrete versus steel, has not been evaluated in a drainage culvert wildlife study to our knowledge.

Environmental variables in drainage culvert wildlife studies most often focus on the natural surroundings of the immediate vicinity of a drainage culvert. For example, variables commonly included in studies are the distance from the culvert entrance to the nearest habitat cover (Clevenger et al. 2001), adjacent habitat types (Ascensão & Mira 2007), the presence of vegetation at the culvert entrance (Grilo et al. 2008), and presence of a soil-based substrate culvert bottom (Glista et al. 2008). While some aspects of water within culverts have been investigated, including stream width (Grilo et al. 2008), no study to our knowledge has analyzed the effect of water level at the drainage culvert entrance on its use by animals. Similarly, rain level has not been included in a study of this nature to our knowledge. Lastly, while the brightness, or luminosity of the moon has been analyzed in unrelated studies (Penteriani et al. 2013; Griffin et al. 2005) with results suggesting that animal activity changes dramatically with the moon's luminosity, its inclusion as a variable in a wildlife passage study has yet to surface. For full list of variables used in this study, see Table 2.

Conclusion

By combining the data of wildlife crossing structure visits by mammals measured using trail cameras, track boxes to determine crossing structure performance indices, and wildlife mortality data on the road surface, researchers can develop an accurate picture of the effect that a given road has on animal movement. Depending on the strength of the data, recommendations may be given to decision makers on how to better mitigate the negative effects that roads have on animal populations. In any case, studies implementing some or all of these methods will add to a larger discussion of the importance of the connectivity of habitat patches in an increasingly fragmented landscape.

MANUSCRIPT

How do ambient and structural variables influence the entry into and full passage of drainage culverts by mammals and their ability to act as wildlife passages?

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ABSTRACT

Roads present a significant barrier to wildlife movement for many species. While designated wildlife crossing structures have been advocated as an attractive solution to many of the problems associated with roads, they are often prohibitively expensive. Autoroute 10 in Southern Quebec is one of many highways in Canada that would benefit from such structures, but currently has none in place. However, the highway has a series of periodically placed drainage culverts designed to allow water to cross underneath the road surface. Through monitoring trail camera footage inside of 13 drainage culverts, and animal track stations along a 20 kilometre stretch of highway A10, this project aims to (1) determine what factors influence the number of full passages of drainage culverts by mammals, and (2) parse the effects that these factors have on the entry into and subsequent full passage of drainage culverts by individual animals. Overall, 20 species were observed outside of the drainage culverts in this study, but only animals highly tolerant to water, including raccoons and American mink, were observed fully crossing the structures with regularity. Water level and polyethylene as a construction material were the strongest deterrents for both the number of full passages, as well as entry into the culverts. Additionally, we found that many factors influenced an individual entering a culvert, while no variables impacted its full passage once it had entered.

In this study, we introduced zero-inflated negative binomial generalized linear mixed models as a statistical method in a road ecology study, analyzing the effects that variables have on excess zeros in the

data, as well as the value of combining trail camera data inside of drainage culverts with track data in the adjacent habitat. We conclude that drainage culverts are ultimately not suitable substitutes for designated crossing structures for mammals, and recommend that where it is not feasible to install designated wildlife crossing structures, dry ledges be installed in existing drainage culverts to better allow small- and medium-sized mammals to safely cross under the road surface while avoiding the water inside of them. Future road ecology studies are needed along all major highways, both with and without mitigation measures already in place, to better understand the effects that roads are having on wildlife. This study was conducted in collaboration with Appalachian Corridor, a non-profit conservation organization dedicated to protecting biodiversity, habitats, and ecological connectivity in the Appalachian region of Southern Quebec.

Introduction

With road development expected to increase by up to 4.7 million kilometres globally by the year 2050 (Meijer et al. 2018; Dulac 2013), wildlife populations and ecosystem health will become increasingly strained unless major mitigation efforts are made. The effects of roads on wildlife are numerous; animal mortality on roads presents a substantial threat to the populations of many species without the presence of proper fencing and crossing structures (Fahrig & Rytwinski 2009), and can lead to the disruption of wildlife movement (Grilo et al. 2008). In many cases, roads create a barrier effect for wildlife that makes it difficult for them to cross (Yanes et al. 1995). An increasing road density means that these barriers are closer together, decreasing the average "roadless" patch size available for animals to move within (Pardini et al. 2017). This has major effects on the movement behavior of many species, with considerable decreases in distance travelled within areas of high human footprint (Tucker et al. 2018). Large mammals with extensive home ranges are affected most heavily (Ng et al. 2004). This decrease in movement can lead to changes in the genetic flow within as well as between populations, and in some cases leads to genetic isolation or local extinction (Banks et al. 2005, Mata et al. 2008).

One measure for mitigating the negative effects of roads on animals is the wildlife passage. It has been supported for its effectiveness at encouraging wildlife to safely cross roads, as well as its ability to educate and engage the public regarding conservation efforts (Niemi et al. 2014). Wildlife passages are structures designed to allow animals to cross either below or above the road surface, and if used in combination with wildlife fencing can drastically reduce wildlife-vehicle collisions (Beben 2012; Rytwinski et al. 2016). By placing wildlife passages and fences along roads that present a barrier to wildlife, movement between habitat patches on either side of the road is increased while lowering the risk of collision between animals and motorists (Marangelo & Farrell 2016). These structures have been implemented as early as 1950. Today, passages are in place around the world (Cramer & Bissonette 2005).

Canadian case studies have been shining examples in the world of road ecology, among them a series of under- and over-passes in Banff National Park in Alberta (Clevenger & Barrueto 2014).

However, while wildlife passages are an attractive solution to many of the ecological problems posed by roads, they are often prohibitively expensive, making them unattainable in many areas (Ruediger 2001). In such situations of financial constraint, it becomes important to explore cost effective (yet still functional) alternatives to wildlife passages, while highlighting regions of importance to focus future efforts (Rodriguez et al. 1996, Bissonette & Adair 2008).

Drainage culverts have received increasing attention for their potential as pseudo-wildlife-passages, allowing for an existing network of tunnels along highways to facilitate animal movement while serving their original purpose of water drainage. It is their ubiquity that shows the greatest potential; an even spacing of tunnels under roads, some conceivably at preferential crossing locations, may already be mitigating the effects that roads have on animals to some degree, and may be improved upon with retrofitting (Grilo et al. 2008, Krawchuk et al. 2005). Indeed, drainage culverts have been suggested as a cost-effective alternative to wildlife passages when funds for large projects are not present (Mata et al. 2008). Wildlife has been observed regularly using drainage culverts to cross under roadways, lending support to this argument (Ascensão & Mira 2007).

However, can drainage culverts truly act as substitutes for wildlife passages? Ascensão et al. (2016) found that road mortality of small mammals was lower in areas where drainage culverts were present, suggesting that in some cases they act as effective ad-hoc passages. However, the intended purpose of the drainage culvert may prove to be its undoing as a passage for wildlife: it facilitates water movement. In many cases aquatic mammals are the only visitors to drainage culverts, with primarily terrestrial mammals avoiding them altogether (Marangelo & Farrel 2016). Still, for some species drainage culverts may be critical for maintaining habitat connectivity (Clevenger et al. 2001), making them a potentially valuable conservation tool that deserves more in-depth analysis. Furthermore, with projected increases in the frequency and severity of storms due to anthropogenic climate change, most drainage culverts will need to be repaired or replaced to properly deal with flooding (van Vliet et al. 2013). This presents an opportunity to install wildlife-friendly features such as dry ledges in an attempt to improve the drainage culvert's ability to move both water and wildlife.

Ecological corridors, linear segments of habitat that allow for the transfer of individual plants and animals across patches otherwise separated by matrix, have been demonstrated to be invaluable tools in conservation for maintaining habitat connectivity in an increasingly fragmented world (Hilty et al. 2006; Pino & Marull 2012). Proposed ecological corridors, those corridors identified using remote sensing technology but not validated on-site, provide useful theoretical information regarding which areas should be prioritized for conservation efforts. Our study area contains seven proposed ecological corridors which may result in higher levels of animal activity for drainage culverts laying within them.

Drainage culverts are made of various materials, each of which provide different benefits at different price points. While concrete drainage culverts are extremely durable, they are expensive to create. Steel, while more affordable than concrete, has a lower weight threshold that can result in their collapse.. Lastly, polyethylene culverts have emerged as an inexpensive alternative to those made of steel. No study to our knowledge has analyzed the difference these materials may have on their use by mammals, and this information could be very informative for wildlife-minded road planners.

To determine the suitability and ultimately the substitutability of drainage culverts to designated wildlife crossing structures, we posed three research questions: (1) which drainage culvert characteristics affect the rates of full passages by mammals? Individuals from which species fully cross, and how often? For individuals that are detected outside of the passage, what factors influence their (2) entry and subsequent (3) full passage of drainage culverts? To answer these questions, we evaluated the relationship between culvert use by mammals and 12 explanatory variables related to characteristics of the drainage culverts and their immediate surroundings (for full list see Table 2). These variables can generally be divided into two categories: structural characteristics and surrounding environmental characteristics.

Structural characteristics often include physical dimensions of the drainage culvert (Seiler et al. 2003; Ng et al. 2004), as well as the type of structure (Mata et al. 2008). To our knowledge, structure material has not been included in a study of this nature before, but has been included here due to the fairly even distribution of materials used to construct the drainage culverts in our study area, and the personal observation that structures made with concrete echoed less and had greater traction, factors which may influence an animal's willingness to cross. Surrounding environmental variables used in past studies include the distance from a culvert entrance to the nearest forest edge (Clevenger et al. 2001), and water-related variables (Grilo et al. 2008). While Grilo et al.'s (2008) study analyzed the effect of stream width on mammal use of drainage culverts, we were more interested in the effect that water depth might have on the behavior of mammals in our culverts, a variable that to our knowledge has not yet been included in a study of this type. The effect of the luminosity of the moon has been included in unrelated wildlife studies (Penteriani et al. 2013; Griffin et al. 2005) with results suggesting that the activity of animals changes dramatically with the moon's luminosity, however its inclusion as a variable in a wildlife passage study has not yet been discovered by the authors. All other environmental variables used in this study have not been included in past wildlife passage studies. For full list of variables used in this study, see Table 2.

We hypothesized that (1) the number of full passages will be largely influenced by water level (-), the distance from culvert entrance to habitat edge (-), length of the culvert (-), and the presence of proposed ecological corridors (+), (2) the factors influencing entry of culverts will be the distance from the culvert entrance to habitat edge (-), culverts constructed with concrete (+), as well as water level (-), and finally, (3) the factors influencing an individual fully crossing a culvert once it has been detected entering will be culvert length (-), culverts constructed with concrete (+), and water level (-) inside of the culvert.

Methods

Study area

The project area lies within a small portion of the Appalachian/Acadian ecoregion. Encompassing areas of New Brunswick, Nova Scotia, Prince Edward Island, southern Quebec, and most of the north-eastern United States, the Appalachian ecoregion houses 5.4 million people while maintaining areas of old-growth forest (Anderson et al. 2006; Appalachian Corridor 2018). More specifically, the Quebec portion of the Appalachians has a human population of 700,000, and is characterized by slowly rolling hills and valleys, the remnants of a former chain of mountains that came into being some 480 million years ago (Li & Ducruc 1999).

The Quebec Appalachians vary considerably in elevation, ranging from sea level to over 1200 metres, resulting in a wide variety of habitat types. Vegetation in this area transitions from forests of sugar maple (*Acer saccharum*) and yellow birch (*Betula alleghaniensis*) to alpine tundra dramatically (Li and Ducruc 1999). This shift in ecosystems provides ample habitat types for many species, resulting in a high species richness in the area. Within the Quebec region of the Appalachians alone, mammals include, among others, bobcat (*Lynx rufus*), Canada lynx (*Lynx canadensis*), moose (*Alces alces*), caribou (*Rangifer tarandus*), North American river otter (*Lontra canadensis*), fisher (*Martes pennanti*), and American marten (*Martes americana*) (Li & Ducruc 1999).

The highway of interest in this study was Quebec's autoroute 10, the province's fourth longest highway at 147 kilometres, stretching from Montreal in the north-west to the south-east-lying city of Sherbrooke (Fig. 1). Fragmenting ecologically important regions including northern Estrie and Monteregie, autoroute 10 was opened to motorists in 1964. The highway borders the southern boundary of Parc national du Mont-Orford, an IUCN category II national park. The portion of autoroute 10 encompassing the study area between kilometre markers 82 and 114.6, encompassing 13 drainage culverts (Tab. 2), received on average 30,950 vehicles per day in 2017 according to data from the Quebec Ministry of Transport. Species killed most often by passing vehicles on this road include North American Porcupine (*Erethizon dorsatum*), whitetail deer (*Odocoileus virginianus*), and unidentifiable micromammals (Quebec Ministry of Transportation, unpublished data; LoScerbo et al., subm.) (Fig. 1).

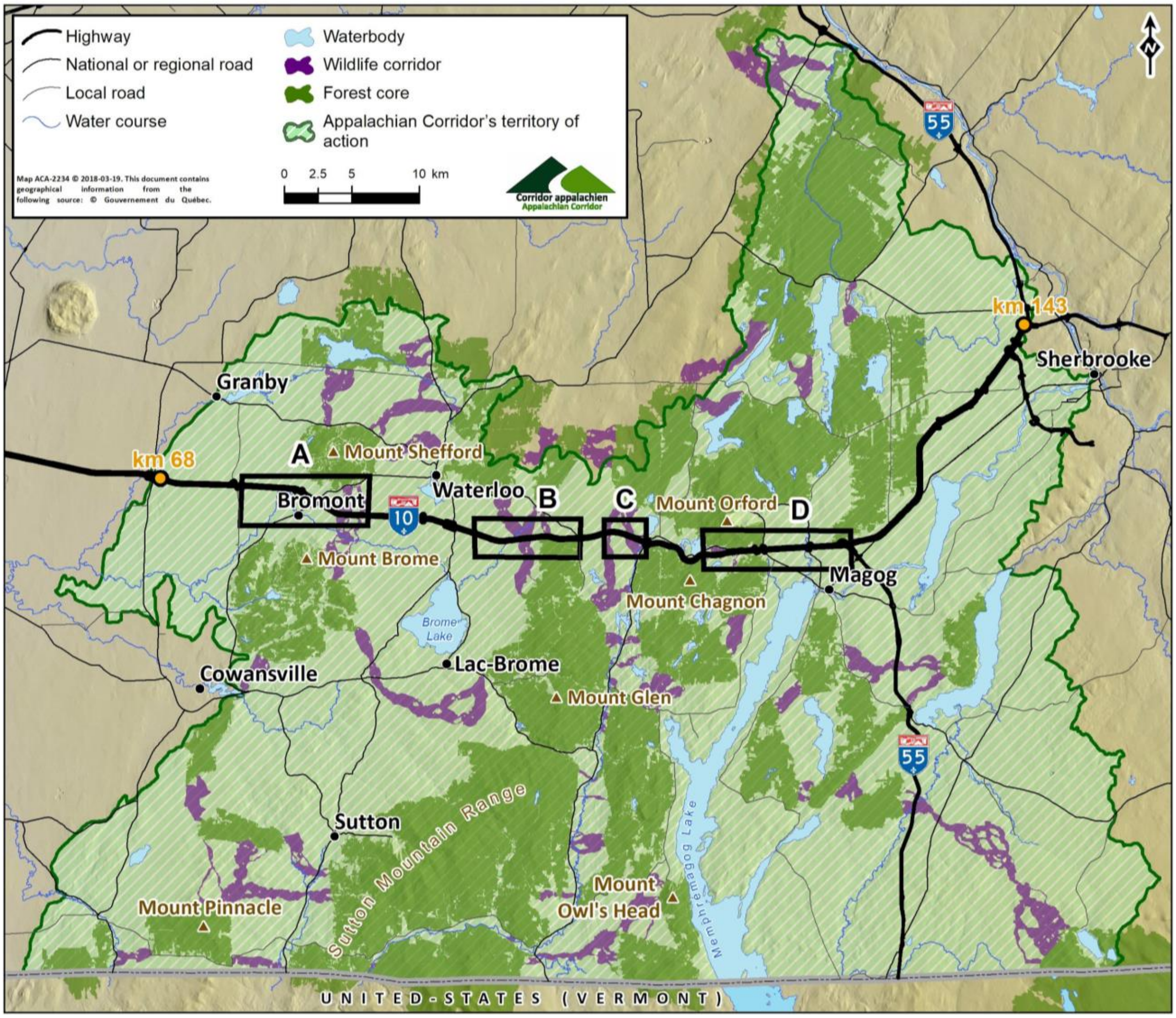

Fig. 1: Map of study area. Western boundary is approximately 80 km from Montreal, Quebec (Courtesy of Corridor Appalachian).

Tab. 1: List of characteristics of 13 drainage culverts studied.

Site	Length (m)	Width (m)	Height (m)	Shape	Material	Inside of corridor?	Average distance from culvert to forest (m)
M6	130.40	1.70	1.70	Circular	Steel	Yes	0
M7	50.00	1.05	1.05	Circular	Polyethylene	Yes	8.50
2	62.50	1.20	1.20	Circular	Steel	No	1.30
3	102.90	1.50	1.50	Circular	Polyethylene	No	0
4	89.00	1.00	1.00	Circular	Polyethylene	No	0
8	56.80	0.95	0.95	Circular	Polyethylene	No	17.80
11	56.00	1.00	1.00	Circular	Polyethylene	No	9.60
14	64.50	1.80	1.80	Circular	Concrete	No	0
15	60.85	1.35	1.35	Circular	Concrete	No	0
17	63.70	1.50	1.50	Circular	Concrete	Yes	0
21	57.00	0.80	0.80	Circular	Polyethylene	Yes	8.83
22	47.50	1.25	1.25	Circular	Polyethylene	Yes	3.50
28	63.50	6.00	3.00	Rectangular	Concrete	No	5.75

Fig. 2: Trail camera installation photos. (Photo credit: Above: Jonathan Cole. Below: Steffy Velosa)

Trail cameras

To measure animal activity inside and outside of the culverts, this project used Reconyx Hyperfire model HC600 motion-sensing infrared trail cameras at each entrance (four cameras per culvert, see Fig. 2 for photos of installation). Trail camera data allowed us to determine full drainage culvert passage rates (where the animal crosses entirely from one entrance of the structure and exits out of the other without turning around within ten minutes) compared to total visits, which include outside presence of wildlife, explorations (where the animal enters through one entrance and turns around, exiting out of the same entrance from which it entered), unknown passages (where the outcome of the visit, due to technical issues or non-detection due to high speed of the moving animal, is not known), and detections outside of the drainage culvert. These numbers provide an approximation of what proportion of animals are able to successfully use the structures to cross under the road. Unknown passages were excluded from statistical analyses.

Full crossings were confirmed if an individual was seen on at least one camera from each entrance crossing completely from one side to the other. Any combination of camera detections were permitted to confirm full passages, including all four cameras, both inside-facing cameras, both outward-facing cameras, or combinations of these (Fig. A.5). Our count dataset was constructed by taking the sums of full crossings, outside detections, explorations, and unknown passages per two-week sampling period, respectively, per species, per site.

Due to financial constraints, we did not have the number of cameras required to have one inward facing and one outward facing camera at each of the thirteen structure entrances simultaneously. We found a solution to this issue by rotating the cameras between every other site on a two-week rotation schedule (Fig. A.3). To minimize the detection bias resulting from differences in detection sensitivity that may be present in any given camera, potentially resulting in the failure of a camera to detect the presence of an animal (Jumeau et al. 2017), this project employed a continuous counter-clockwise rotation of cameras among sites. Every two-week session, cameras were moved to their counter-clockwise neighbour, resulting in each structure hosting a different set of cameras for each sampling period. Data collected at any given structure was stored on SD cards labelled with the structure’s ID to ensure organization during the rotation process.

Track boxes

Animal footprint collection was employed as a tool to estimate species presence in the forest adjacent to the drainage culvert sites. Two footprint-collecting track boxes were placed outside of each structure entrance, 40 meters away from the entrance on either side of the structure, and an additional 20 meters away from the road surface in the adjacent habitat (Fig. 3). The goal of these track boxes was to detect individuals within the adjacent habitat away from the highway as a rough index of mammal activity, including animals that may not venture out into the cleared shoulder of the road.

Track boxes were constructed using two bent sheets of corrugated black chloroplast fastened with tape and wooden poles to form a rectangular enclosure following the construction plan by Bélanger-Smith (2014) (Fig. 4). A thin layer of white polystyrene was fastened inside the bottom of the track box, proving a surface on which to attach the track papers. A layer of ink was applied to each entrance of the box, with brown kraft paper placed in the center of the box, both of which were replaced bi-weekly. The ink was formulated using activated cosmetic charcoal powder and mineral oil, at a ratio of 0.5 cups of powder to 1 litre of oil. To attract mammals, a lure was placed into the box as inspired by Bélanger-Smith's (2014) study: a mixture of fish oil, anise oil, and a carnivore lure called K-9 Triple Take made by Forsyth Animal Lures. The lure was poured bi-weekly into red solo cups taped to the inside wall of the track box, and formulated using a ratio of 0.25 cups of fish oil to one tablespoon of anise oil to one popsicle-stick-dab of carnivore lure (further details in App. A).

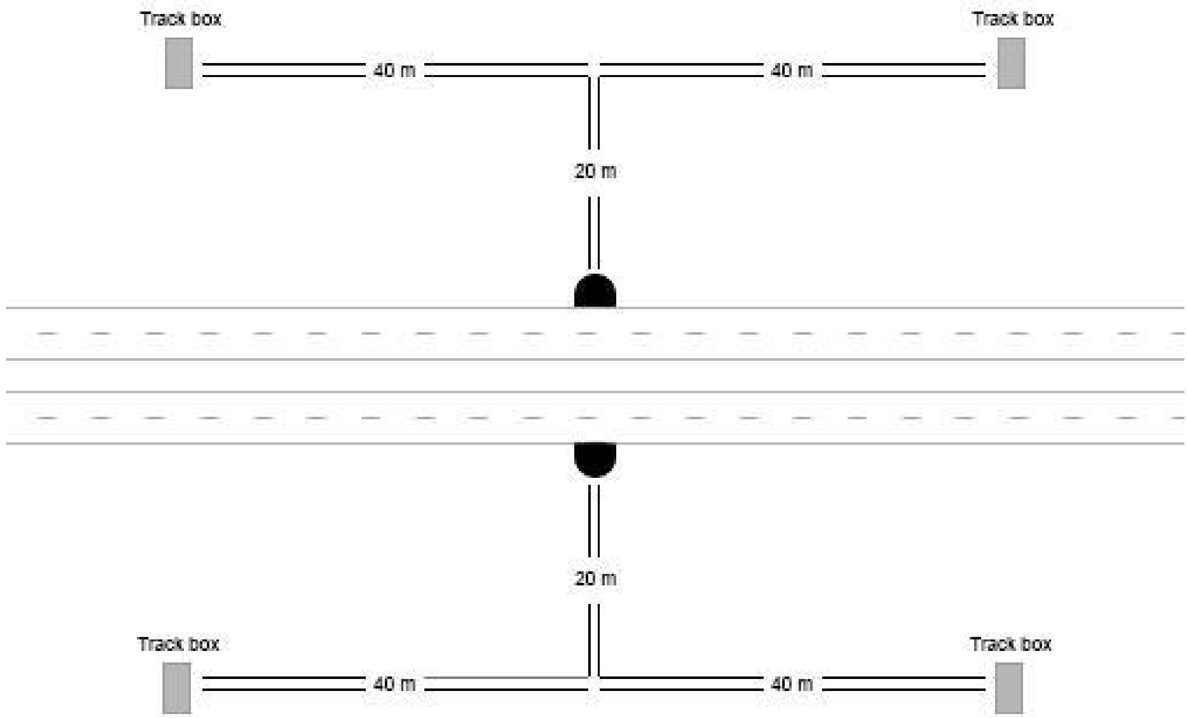

Fig. 3: Trackbox layout in relation to each drainage culvert.

Fig. 4: Track box preparation photos. (Photos: Mehrdokht Pourali)

Variables considered

Due to the differences in time measurements between research question 1 (two-week sampling periods) and research questions 2 and 3 (daily sampling), several variables were selected or altered to better suit each research question (Tab. 2). For example, “track.avg”, the average number of tracks detected per site per two-week period for each species, was only able to be included in the model for research question 1 due to the two-week frequency of track papers collected. Similarly, “avg.rain (cm)”, representing the two-week average rainfall in the study area, was used only in the model for research question 1, while “rain (cm)”, the daily rainfall measurement, was employed in the models for research questions 2 and 3. All other variables were used in all three models.

Tab. 2: Variables considered in the analysis of the drainage culverts (*n* = 13) monitored along Highway A10, Quebec, Canada in summer 2018.

Variable name	Definition / explanation and units	Range of values	Related to research question	Variable type
material	Culvert material	Steel, polyethylene, concrete	1, 2, 3	Fixed
dist.forest	Distance from culvert entrance to habitat edge (m)	0 - 17.80	1, 2, 3	Fixed
track.avg	Average number of tracks detected per species per site (referred to as “tracks” in text)	0 - 0.50	1	Fixed
temp	Average temperature per two-week sampling period(°C)	-3.36 - 20.93	1,	Fixed
daily.temp	Daily temperature measurement from nearest weather station (°C)	-9 - 32	2, 3	Fixed
week	Two-week sampling session of each data point	1 - 7	1, 2, 3	Fixed
corridor	Whether or not the site lies within a proposed ecological corridor	0 - 1	1, 2, 3	Fixed
length	Structure length (m)	47.50 - 130.40	1, 2, 3	Fixed
water	Water depth at culvert entrance (cm)	0 - 55	1, 2, 3	Fixed
avg.rain	Average precipitation per two-week session (cm)	0 - 15.4	1	Fixed
rain	Precipitation per day	0 - 38.1	2, 3	Fixed
qmoon	Quantified moon cycle	0 - 1	2, 3	Fixed
site	Drainage culvert ID	13 sites	1, 2, 3	Random
species	Species of each data point	-	1, 2, 3	Random

Statistical analysis

All models used in the analyses were tested for multicollinearity using variance inflation factors (VIF) (Alin 2010). A common rule of thumb states that if any variable returns a VIF coefficient of 10 or greater, the variable is considered to be collinear with at least one other variable (O'Brien 2007). However, we followed Ringle et al.'s (2015) more rigorous VIF threshold of 5 to ensure there was no multicollinearity within our datasets and to avoid any unreliable parameter estimates (Mansfield & Helms 1982) (Tab. B.5).

We performed model selection for fixed effects by stepwise backward model reduction (Zuur et al. 2009) and compared models using Akaike's Information Criterion (AICc) (Hurvich & Tsai 1989). When a model excluding a given variable resulted in an AICc score difference of two points or greater (indicating a lower degree of parsimony) compared to the global model, the variable was considered significant and was inserted into the final model. This was performed for each fixed effect in the global model until all variables were either discarded or included in the final model. We acknowledge the criticisms calling for the cautious use of stepwise model reduction (Flom & Cassell 2007), but elected to use the method for its computational efficiency, clear interpretation, and its very common usage in the field of ecology (Zuur et al. 2009, Alexandre et al. 2018).

Zero Inflation

To address research question 1, we modeled full drainage culvert passage counts of mammals per two-week sampling period (n = 7) using zero-inflated negative binomial (ZINB) generalized linear mixed models (GLMM) to assess the effect that some variables may have on making sites inaccessible to mammals. Our count data of full passages exhibited considerable overdispersion (overdispersion parameter = 2.2, p = 7.3e-60, with zeros comprising 87.76% of the data for outside presence and 89.95% for full passages), necessitating the use of negative binomial regression. Because we suspected that some variables (water depth and the distance between the drainage culvert entrance to the nearest habitat edge) may be causing absences (called structural zeros) separate from those naturally occurring (called true zeros) due to the low population densities of some mammals in our study area, zero inflation was utilized for its ability to assess which component in a model may be causing structural zeros. Generally, zero-inflation is used when there is a significant excess of zeros that is higher than the number that would be expected according to a Poisson or negative binomial distribution, leading to overdispersion (Zuur et al. 2009). Studies over the past five years have shown that statistically ignoring the presence of zero inflation in count datasets often causes bias in the estimation of parameters and leads to inaccuracies in model interpretation (Bouyer et al. 2015).

We estimated coefficients using maximum likelihood under R version 3.3.3 (R Core Team 2017) with the package *glmmTMB* (generalized linear mixed models using Template Model Builder) version 0.2.3 (Brooks et al. 2017, Alexandre et al. 2018). Structurally very similar to the package *pscl* (Zeileis et al. 2008), *glmmTMB* allows for the estimation of correlation within sampling units (random effects) through mixed models, of which *pscl* is not yet capable (Brooks et al. 2017). The *glmmTMB* zero-inflation model has two central components: (1) a conditional model that reports the coefficients of the negative binomial generalized linear mixed model using the same syntax as *lme4* (Bates et al. 2007), and (2) a zero-inflation component that reports the probability of a fixed effect resulting in the observation of an extra zero that is not generated by the conditional model (Brooks et al. 2017).

To account for repeated measurements at both the species and site scales, categorical variables “species” and “site” were included in the model as random effects. Only species with at least fifteen detections were included in this analysis to reduce zero-counts, resulting in seven species: common raccoon (*Procyon lotor*), whitetail deer (*Odocoileus virginianus*), American mink (*Neovison vison*), eastern grey squirrel (*Sciurus carolinensis*), weasel spp. (including *Mustela nivalis*, *Mustela frenata*, and *Mustela erminea*), muskrat (*Ondatra zibethicus*), and red fox (*Vulpes vulpes*). To account for potential temporal variation in mammal activity, a numeric value for each two-week sampling period was included as a fixed effect in the global model.

Logistic Regression

For mammals that were detected by trail cameras outside of the drainage culverts (for research questions 2 and 3), we modeled binary outcomes for both entry into and full passage through the culverts with logistic regression using generalized linear mixed models with binomial distributions and logit links. Through this method, we determined which structural and environmental factors affect entry into, and once inside, which factors affect full passage of drainage culverts by mammals. Generalized linear mixed effects models were required for this data type due to the non-normal binomial distribution. Additionally, the random effects of the model required a mixed model type. All statistical tests for this section were performed in R version 3.3.3. (R Core Team 2017) with the package *lme4* (Bates et al. 2015).

As before, repeated measures of species and sites were accounted for by including them as random effects. Moon luminosity as a function of the moon phase has been shown to affect the movement of some species (Prugh & Golden 2014; Penteriani et al. 2013). To account for this potential effect, moon luminosity was included as a fixed effect. See Table 2 for full list of variables considered.

Results

Across 13 sites and 99 observation days, we collected a total of 193,867 trail camera photos that included a total of 1145 unique animal detections, 261 of which resulted in a full crossing (22.79 %; Appendix B). Detections spanned 20 species (Figs. 5 & 6), though only species with at least 15 detections were included in further analysis for research question one. Common raccoons (*Procyon lotor*) fully crossed drainage culverts most often (37.54% of interactions with drainage culverts resulted in a full passage, 217 full crossings out of 587 detections), 2.8 times more likely to make a full crossing than the next highest full crossing species, the American mink (*Neovison vison*) (13.39%, 17 full crossings out of 127 detections). Species of special interest that were detected inspecting the drainage culverts included 3 observations of bobcats (*Lynx rufus)* and 3 observations of black bear (*Ursus americanus*), but no full crossings were attempted. Trackboxes detected 15 species, with mouse spp., Eastern gray squirrel (*Sciurus carolinensis*), and common raccoon (*Procyon lotor*) being the most commonly detected species (Fig. 7).

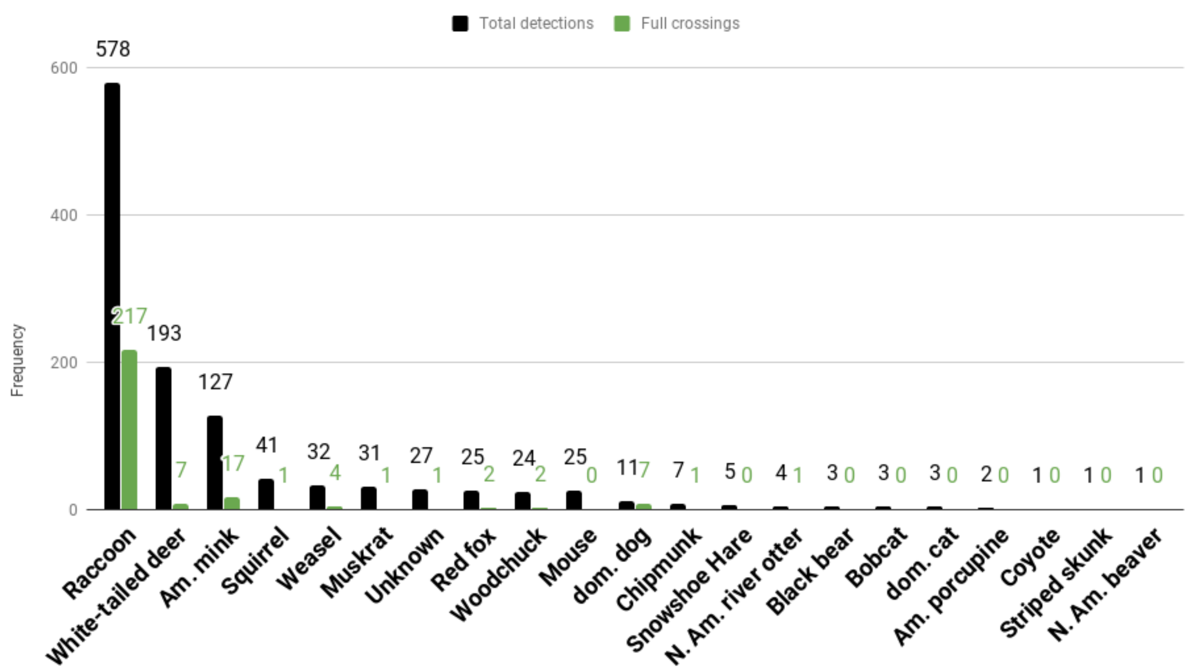

Fig. 5: Total number of detections and full crossings by species.

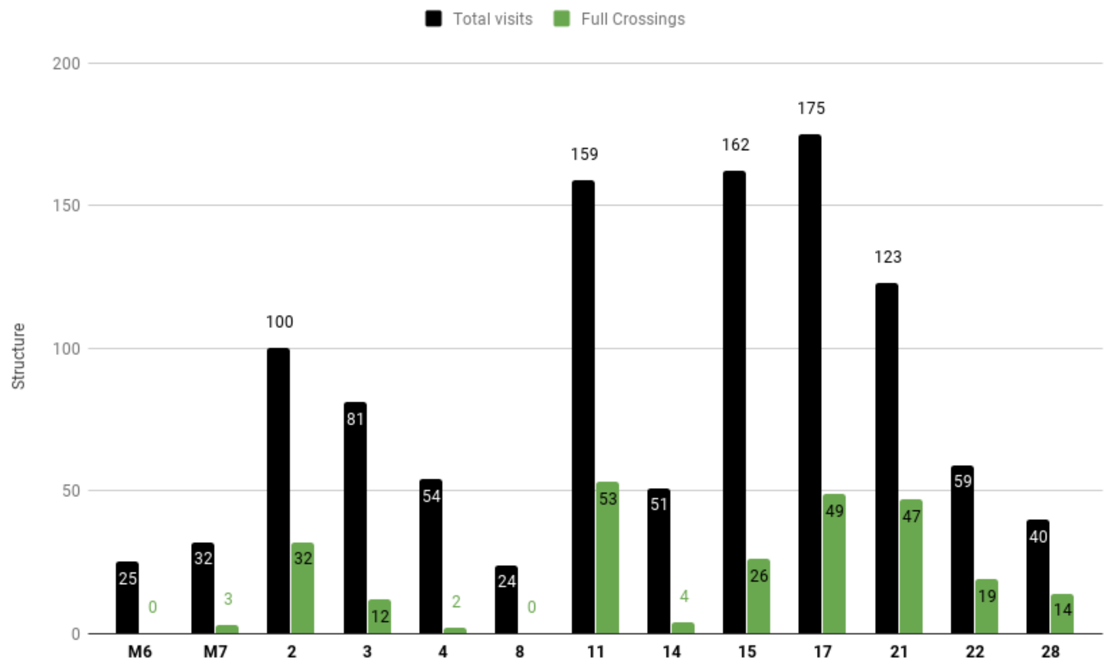

Fig. 6: Total number of detections and full crossings per drainage culvert site.

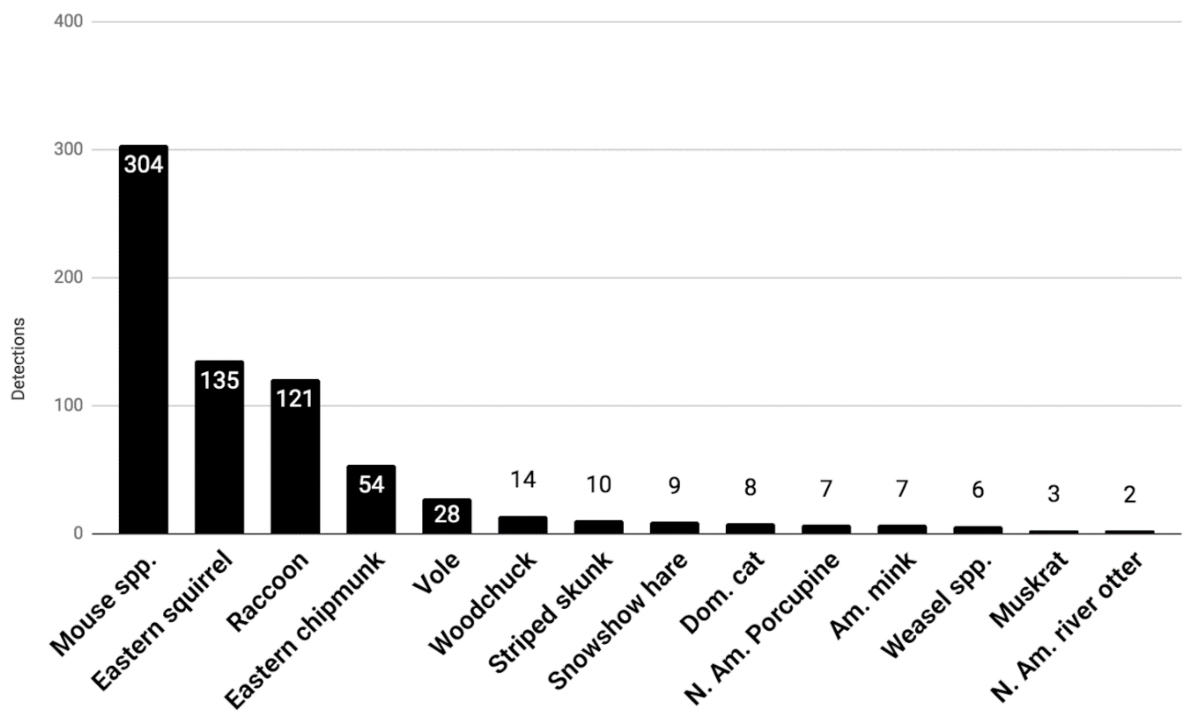

Fig. 7: Total number of trackbox results by species.

Table 3. Results of model-selection procedure evaluating number of full crossings, entry success, and crossing success by mammals over seven two-week sampling periods. The most parsimonious model is indicated with an asterisk.

Dataset	Model[a]	df[b]	LLR[b]	AIC_c[b]	R^2[bc]
Full crossings per two week session Negative binomial (count)	Tracks + temp + week*	10	-253	526	-
	Material + dist.forest[d] + tracks + temp + week + corridor + log(length) + water + rain	17	-250	533	-
Outside detections that lead to entry Logit (binomial)	Material + log(dist.forest+1) + water + moon*	8	-93.4	203	0.82
	Corridor + material + log(dist.forest+1) + log(length) + water + moon + temp + log(rain+1)	12	-90.2	204	0.76
Inside detections that lead to full crossing Logit (binomial)	Corridor + log(dist.forest+1)*	5	-29	70	0.09
	Corridor + material + log(dist.forest+1) + log(length) + water + moon + temp + log(rain+1)	12	-27	78	0.19

[a] See Table 2 for further variable details.

[b] Degrees of freedom (df), Log Likelihood (LLR), Akaike's Information Criterion adjusted for small sample size (AIC_c), and conditional pseudo-R^2 value.

[c] Pseudo-R^2 values not shown for ZINB GLMM because this statistic is not suitable for two-step regression models.

[d] The distance to forest variable was not log-transformed for research question one due to model convergence errors.

Number of full crossings per two week period

The ZINB GLMM model containing only three variables after stepwise model selection (Zuur et al. 2009) was more parsimonious than the global model (Table 3), and included tracks per species per site per sampling unit, temperature, and week as fixed effects, with site and species kept as random effects. We collected a total of 638 two-week sampling period data points across our sites from which we ran our statistical analysis. We found that excess absences of full crossings significantly rose as a result of water level ($\beta = 0.13$ [0.03 to 0.23], $P = 0.01$), while no significant effect on excess zeros was measured by the distance from a drainage culvert entrance to the nearest habitat edge (Table 5). These excess absences of full crossings resulting from water level (or excess "true" zeros) mean that the zero-inflation model predicted that due to the level of water at each site, animals were not able to enter the detection zone by the trial cameras, resulting in an inflated number of zeros in the data. With absences accounted for, the number of full passages per species was found to be higher when tracks from that particular species were also detected in the adjacent habitat (β = 5.52 [1.69 to 9.35], *P* = 0.005), as well as when temperatures were higher (β = 0.10 [0.05 to 0.14], *P* = <0.001). Sampling period did not have a significant effect on full passages. Unexpectedly, culvert material, the distance from culvert entrance to forest edge, the presence of a proposed ecological corridor, the length of the culvert, and average two-week rain level were not selected for the final model.

<u>Entry into and full passage of drainage culverts</u>

For estimating which factors influenced the entry of mammals that were first detected outside of drainage culverts, the model containing only variables selected during the model selection process was marginally better performing than the global model (Tab. 3). A total of 409 outside detections across 15 species were collected across all sites throughout the 99 day sampling period. Comparing conditional pseudo-R^2s revealed that the final model explains 6% (global model R^2 = 0.76, final model R^2 = 0.82) more of the data's variance than the global model. Entries into drainage culverts were found to be significantly affected by the material of the structure, with polyethylene negatively affecting entries (β = -3.36 [-5.28 to -1.44], *P* = <0.001), and steel and concrete having no effect. Surprisingly, the distance from the drainage culvert entrance to the nearest forest edge had a positive effect on entries (β = 0.76 [0.22 to 1.30], *P* = 0.006). Environmental factors also significantly influenced entries, with water level negatively affecting entry (β = -0.17 [-0.28 to -0.06], *P* = 0.06) and moon luminosity positively influencing entry (β = 2.25 [0.63 to 3.87], *P* = 0.006). Variables not selected from the global model include the presence of a proposed ecological corridor, culvert length, daily temperature, and daily rain level.

Using a subset of the above dataset containing only detections where the individual animal had entered the drainage culvert (*n* = 78 across 4 species), several models provided an equally reasonable fit following stepwise model selection, and therefore none of them could be discarded. We therefore elected to construct all possible models and use the most parsimonious model (see Table 3). The most effective model contained only the presence of an ecological corridor and the distance from the culvert entrance to the nearest habitat edge as fixed effects, though all models had low pseudo-R^2 values (<0.19). No significant effects were measured to influence the full passage of mammals once they had entered a drainage culvert (Table 4).

Tab. 4: Regression coefficients for final models.

Response variable	Variable	Coefficient	CI	*P*-value
Number of full passages	Track average	5.52	[1.69, 9.35]	0.005
	Temperature (°C)	0.10	[0.05, 0.14]	< 0.001
	Water (cm)*	0.13	[0.03, 0.23]	0.01
	Distance to forest (m)*	-0.25	[-0.93, 0.43]	0.47
Individual culvert entries	Material (polyethylene)	-3.36	[-5.28, -1.44]	0.001
	Material (steel)	-1.07	[-3.37, 1.24]	0.36
	Distance to forest (m)	0.76	[0.22, 1.30]	0.006
	Water (cm)	-0.17	[-0.28, -0.06]	0.002
	Moon luminosity	2.25	[0.63, 3.87]	0.006
Individual full crossings	Presence of corridor	1.21	[-0.31, 2.74]	0.12
	Distance to forest	0.73	[-0.15, 1.62]	0.10

* Indicates zero-inflation coefficient, where positive values indicate the variable's likelihood of producing excess zeros in the data.

Discussion

General results

Our results highlight that despite the multitude of species present near the habitat edge and roadside, only a small fraction of species were documented entering and even fewer fully crossing drainage culverts in our study area. Only common raccoons (*Procyon lotor*), American mink (*Neovison vison*), and whitetail deer (*Odocoileus virginianus*) were observed fully crossing drainage culverts with some regularity during our sampling period, while other species often observed outside of the structures, including weasel spp (including *Mustela nivalis*, *Mustela frenata*, and *Mustela erminea*), red fox (*Vulpes vulpes*), and snowshoe hare (*Lepus americanus*), were rarely if ever observed fully crossing the structures. All of the drainage culverts in our study received entry by mammals, while all but two culverts received full passages (Fig. 6).

Influence of Variables

Animal track data has been an invaluable tool in wildlife studies for decades (Ward 1982; Clevenger & Waltho 2000). When used for assessing wildlife crossing through passages, track stations have acted as a cost-effective method of detecting which species were present in a structure over a given sampling period (Ng et al. 2004). However, using animal tracks as a means of determining full crossings and general behaviour of animals is problematic, in that it is difficult to infer information beyond presence/absence using only the tracks of a species over a given period of time (Seiler & Olsson 2010). Here, we use track data as a method of determining whether species are present in the adjacent habitat to then compare with animal activity in and around the drainage culverts using motion-sensing trail cameras. We found that track data is highly predictive of the number of full crossings observed in drainage culverts. As a fixed-control variable, the average number of tracks found per species per site was found to significantly improve the performance of our ZINB GLMM, accounting for 7.98% more variance of the data within the fixed effects (marginal R^2) than our final model without track data (see Table B.4).

Water level was found to be both negatively correlated with mammal entry into drainage culverts and a source of structural zeros in our count data. This has extremely important implications for drainage culverts as alternatives to wildlife passages; we have shown that the drainage culvert's inherent purpose of facilitating water movement makes it entirely unsuitable as a passage under roads for most species in our study area. While this is a highly intuitive result, and while some studies have discussed the need for alterations to drainage culverts for animals to avoid water (Niemi et al. 2014), very few studies (for instance, Marangelo & Farrell 2016) have quantified the effect that water has on the entry and full passage of drainage culverts by mammals.

The distance from the entrance of a drainage culvert to the nearest habitat edge was found to have a positive effect on the entry of mammals into the structures. This result was surprising due to past research findings that even small clearings in habitat act as impenetrable barriers for many species, small mammals in particular (Clevenger & Waltho 1999; Laurence et al. 2002). Indeed, because density of mammal populations is known to be generally higher away from road surfaces (Pockock & Laurence 2005), we expected that greater distance between a culvert entrance and habitat edge - often indicating an entrance closer to the road surface - would result in fewer entries into culverts by mammals. However, reviewing the results by species reveals that this result may largely be a result of generalist species including common raccoon (*Procyon lotor*) and larger species with greater mobility including whitetail deer (*Odocoileus virginianus*) dominating the dataset that are more tolerant of non-ideal habitat types (see appendix B). Additionally, it could be argued that individual animals that are already within the open "matrix" of the area between the road and the adjacent forest are more likely to fully cross a culvert to quickly leave the open area, or that animals entering the open area between the road and adjacent habitat may already be habituated to the altered area, and may be aware of the location of the drainage culvert's location.

Structure material is rarely considered in wildlife passage studies (for instance, Beben 2012), but due to drainage culverts coming in various shapes, sizes, and materials, we included this variable in our analysis to assess the effect that a drainage culvert's material might have on entry and full passage of mammals. We found that culverts constructed with polyethylene, a sturdy and affordable plastic, strongly deters entry by mammals, while steel and concrete displayed no significant effect on mammal response. To our knowledge the effect of the material of a crossing structure on animal use has not been analyzed before, and has important ramifications for transport ministries and decision makers wishing to consider wildlife-friendly drainage culverts. While polyethylene culverts are a cost-effective alternative to traditionally concrete or steel drainage culverts, decision makers should be wary of them when considering drainage culverts that both facilitate water movement and allow for the passage of wildlife. From observations taken in the field, polyethylene culverts in our study had a distinct plastic smell and were much more slippery than either steel or concrete culverts. While we cannot say with certainty what may be deterring animals from polyethylene culverts, we suspect that a mixture of these factors likely plays a role in their disfavour among wildlife.

Ecological corridors can be essential links between otherwise isolated patches of habitat in an increasingly fragmented landscape (Hilty et al. 2006). We followed the hypothesis that properly functioning ecological corridors should have more animals travelling within them, and that drainage culverts lying within the path of these corridors ($n = 5$) would therefore have more animal activity than those outside of them ($n = 8$). The proposed ecological corridors in our study area were determined in a past study as having potential to act as links between patches of habitat in southern Quebec (Salvant 2017). Our results, however, showed that the presence of proposed corridors plays no significant role in predicting animal presence, entry, or full crossing of mammals through drainage culverts. We suspect that while the proposed corridors certainly have potential to act as linkages between habitat patches, at present they are likely fragmented by roads to such an extent that they are not functioning as proper ecological pathways. This inference is supported by the results of a Welch two-sample *t*-test between the average number of tracks detected within versus outside of the proposed ecological corridors, that did not find a significant difference between the two groups ($t(474.56) = 0.78$, $p = 0.44$).

Indeed, when highways are constructed through ecological corridors, the resulting habitat fragmentation often acts as a major constraint on the movement of animals moving and living within the area (Forman 2005). If the barrier presented by the road is severe enough, animals will not be able to cross in large enough numbers resulting in loss of ecological connectivity and isolation of fragmented habitat patches (Dupras et al. 2016). To help combat this, we recommend constructing wildlife passages that align with the path of ecological corridors, allowing animals moving along them to safely cross the highway without having to significantly deviate from its path (Clevenger & Huijser 2009). In our study area, several culverts are already placed within proposed ecological corridors, and retrofitting these structures to better suit animals should therefore be a high priority. Additionally, constructing wildlife fencing that lead to either drainage culverts or designated wildlife crossings in these corridor areas would be highly useful in lowering the amount of roadkill in these areas, as Rytwinski et al. (2016) found in their meta-analysis.

Moon luminosity was found to have a significant effect on the entry of mammals into drainage culverts. Because the grand majority of animal detections in our study were during the nighttime hours (Fig. 8), it follows that nights with greater moon luminosity - and therefore higher visibility - would result in higher animal activity. The effect that the moon's luminosity has on animal activity has been assessed in other studies (Griffin et al. 2005; Prugh & Golden 2014), but to our knowledge has not been included in an animal study relating to roads until now. We suspect that road mortality would also peak during periods of higher moon luminosity, and we encourage the inclusion of this variable in future roadkill studies.

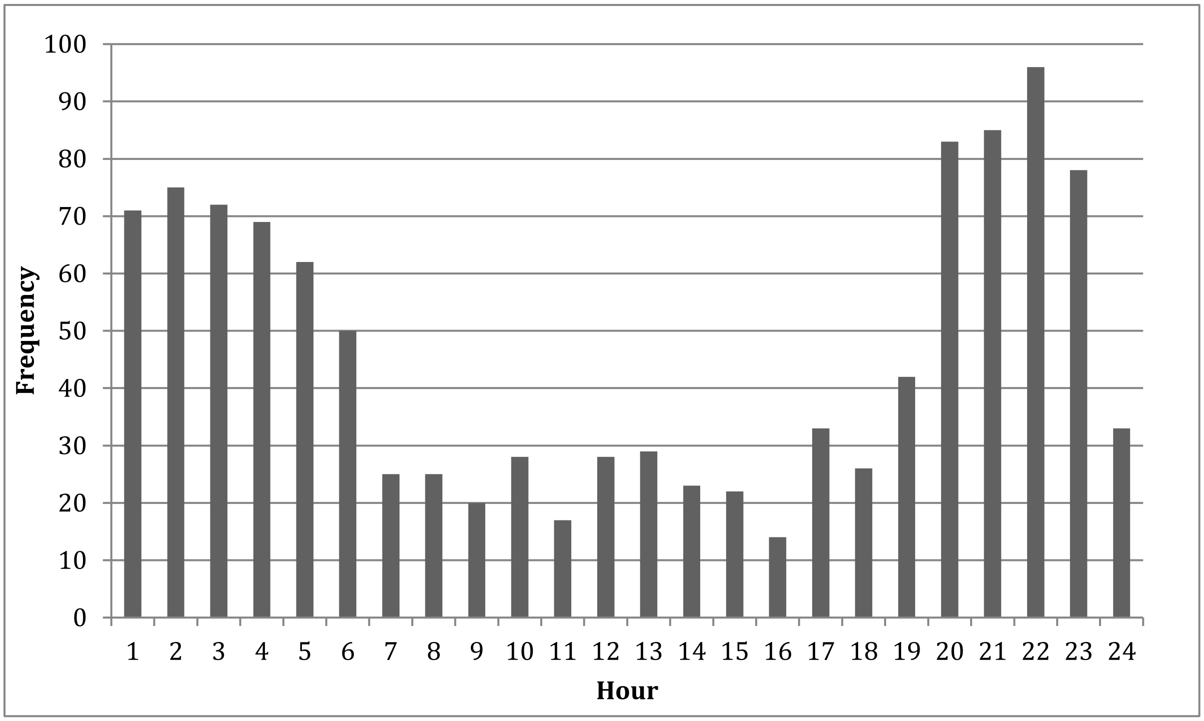

Fig. 8: Time of camera detection across all species.

Species of special interest

Although we observed low numbers of detections from species of special interest, for example black bear (*Ursus americanus*) and bobcat (*Lynx rufus*), their naturally low population densities mean that their detection in our study is still highly significant. Both black bears and bobcats were observed from the drainage culverts' outward-facing trail cameras approaching and investigating the entrance to the structures, but no entries were recorded (see Appendix B). This result is very important as this shows that these species are present along the habitat edge and close to the highway barrier, but found the drainage culverts in our study area to be unsuitable as passages across the road. We strongly recommend the implementation of larger structures that are better able to facilitate the movement of large mammals.

Novel findings and techniques

One of the most intriguing results in our study was finding that for mammals fully crossing underneath highways, many factors influence their entry into drainage culverts, while no effects were found influencing their full passage once inside; factors including water level, structure material, and moon luminosity affect an animal's entry into a drainage culvert, once it was inside, no variables included in our study affected whether it would fully cross. Low pseudo-R^2 values were observed for all of our potential models for this test, with no statistical significance among them. Because of this, we felt confident in selecting the final model for this research question solely by AICc score, due to no variables being significant regardless of the outcome of the model selection process. This result suggests that mammals in our study area consider multiple factors before entering a structure, and that once inside, few factors impact their initial decision. This too has significant implications for wildlife passage planners, as this result suggests that while the passage in its entirety should be designed with care, entrances to wildlife passages should receive the utmost attention to make them as attractive to wildlife as possible. While this "attraction" factor likely differs by species, we can generalize that in this study mammals preferred structures with little to no water running through them, as well as structures that were not constructed with polyethylene. Other studies have found that vegetation around the passage entrance (Clevenger & Barrueto 2014), a soil substrate along the passage floor (Krawchuk et al. 2005), and passages with a high structural openness (Seiler & Olsson 2010) are also strongly favored by many species.

We have assessed the factors affecting mammals' entry and full crossing of drainage culverts while employing several novel data collection methods and statistical techniques. To our knowledge this is the first research project that has (1) used a scheduled rotating motion-sensing camera study design to minimize detection bias present in individual cameras, (2) utilized both outward- and inward-facing cameras to determine outside presence of animals as well as inside of drainage culverts, (3) combined animal track data with motion-sensing camera data to assess the relationship between mammals present in the habitat adjacent to the road versus animals within detection-range of the trail cameras, and finally (4) utilized zero-inflated negative binomial generalized linear mixed effects models to test for the presence of structural zeros in a road-related wildlife study.

One method that is very likely to become standard procedure in ecological studies to determine factors that lead to habitat unsuitability, much like culvert water depth in this study, is the use of zero-inflated modelling. The utilization of zero-inflated mixed models in ecology is currently on the cutting edge of statistical analyses, with only a handful of publications using the method since its creation in 2010 and widespread introduction in 2017 (Brooks et al. 2017; García-Romero et al. 2019; Williams et al. 2018). While the package *glmmADMB* introduced in 2010 (Skaug et al. 2010) allowed for the use of zero-inflated mixed models, it was largely discarded for its inability to handle more than one zero-inflation variable, difficulty with converging models of larger datasets, and prohibitively long run-times. Several of the package's creators took part in the development of *glmmTMB* as a replacement capable of quickly performing all of the tasks its predecessor could not (Brooks et al. 2017). Because ecological studies often have repeated measurements across sites, random effects must be taken into account in regression models in this field, something that was largely not possible with zero-inflated modelling until *glmmTMB*'s introduction. Due to ecologists' interest in not only determining what factors contribute to a response, but what variables may entirely prevent a response from occurring, such as animals not being present in a sampling area, we feel that zero inflated modelling is a natural fit for ecological studies.

Limitations

While this study employed particularly strong sampling techniques, including the use of four motion-sensing trail cameras per drainage culvert, as well as the two-week rotation of trail cameras to reduce the detection bias in individual cameras, it could have benefitted from several small changes to its general design and duration. For example, having a longer sampling period would lend support to a stronger statistical analysis due to a larger sampling period. This study spanned 99 days, with cameras active in each site for half of the sampling period due to the rotation of trail cameras (Fig. 9). However, a longer sampling period in this study would have extended into the winter months, when many of the species in our study area would either be in hibernation or be exhibiting lower activity. Starting the sampling period earlier in the spring season would undoubtedly have resulted in a larger sample size. Additionally, having multiple sampling seasons and a larger number of drainage culverts would potentially further strengthen our findings.

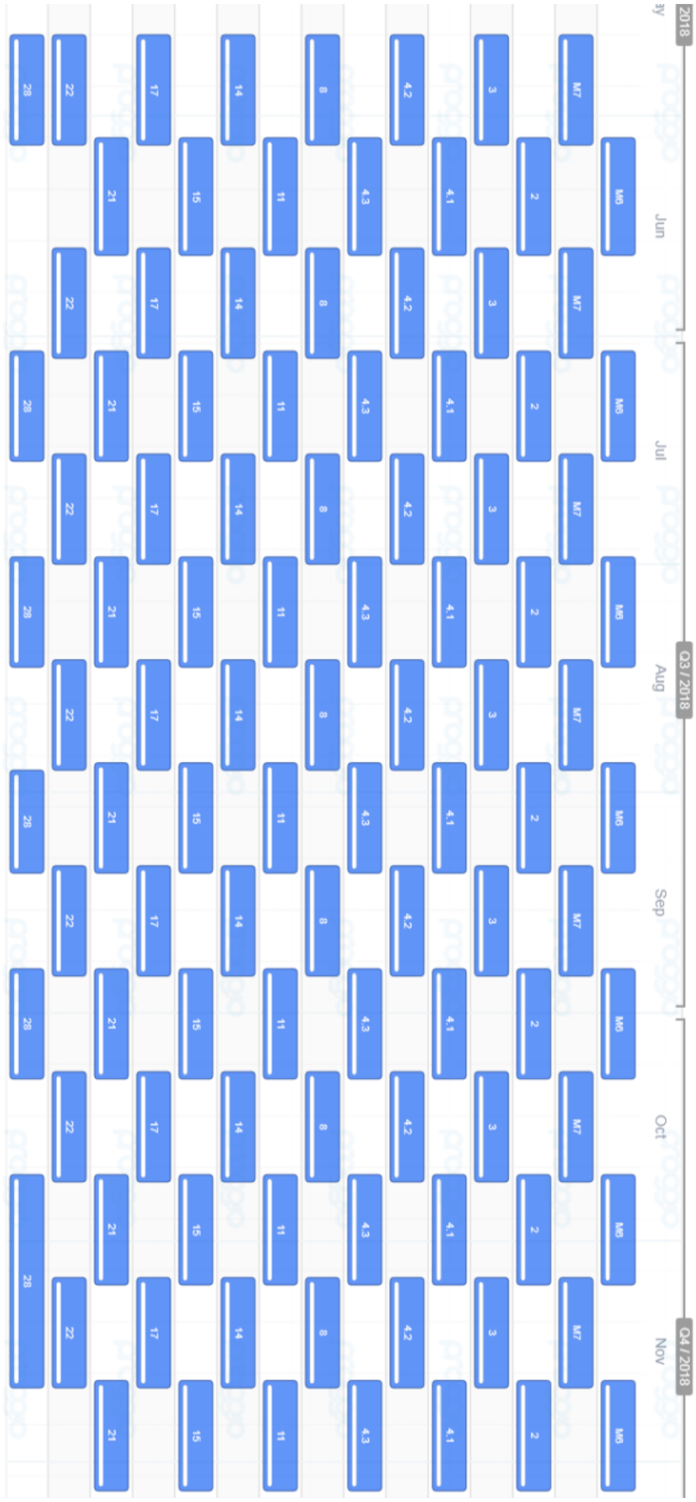

Fig. 9: Camera deployment duration per site.

Although the variation in drainage culvert characteristics including construction material and dimensions was as large as possible given the study area, having a larger sample of drainage culvert materials and sizes would have increased the strength of the study considerably. In particular, this study would have benefitted from a higher number of large box culverts. Because of the small sample of box culverts in this study (*n* = 13), it will be difficult to draw confident conclusions regarding their ability to allow animals to cross through them. In particular, large box culverts in this study showed good potential to allow for the passage of deer and other large mammals of special interest, so increasing the sample size of this type of culvert could have ecologically significant implications.

Suggestions for future research

While wildlife monitoring studies with a one-season sampling period, as this study was, provide ecologically significant information, conducting a multi-timeframe study that assesses the activity of animals both before and after a variable is introduced provides an excellent opportunity to determine the effect that the variable has on the response variable (Rytwinski et al. 2015). Regarding this study's survey area, the potential for the installation of wildlife fencing along the highway presents a unique opportunity to measure both animal activity around the highway as well as animal mortality on the road surface before and after the fence's installation. Ideally, fences would be constructed where roadkill hotspots exist, with fence ends placed in conjunction with existing drainage culverts to allow animals venturing to the end of the fence to cross under the highway. This study design type, known as a before-after-control-impact (BACI) study, has the potential to show the impact that a wildlife fence may have on the movement patterns and mortality on the road surface of mammals along Autoroute 10. These results would be essential for determining the value of such fencing, and would have the potential to influence the installation of wildlife fencing in other areas.

Conclusions and recommendations

For 13 drainage culverts along a high-traffic 4-lane highway in southern Quebec, we assessed the effect that structural and environmental factors have on the entry, full passage, and number of full passages by mammals. In this study we found that, for mammals, (1) the presence of water outside of and within drainage culverts resulted in site avoidance, (2) polyethylene drainage culverts were strongly disfavored, (3) increasing distance from culvert entrance to habitat edge resulted in more entries, (4) the luminosity of the moon had a positive effect on the activity and therefore entry of culverts, and (5) that many more factors play a role in an animal's entry into a drainage culvert than its full passage once it is already inside.

We recommend that wherever possible, dry ledges be installed inside of drainage culverts to allow for mammals to cross through drainage culverts without water levels deterring their passage, in accordance with Glista et al. (2009). Furthermore, retrofitting and conservation priorities regarding drainage culverts should be given to those that already lay inside of the boundaries of ecological corridors. Improving these optimally placed structures could help sustain the proper functioning of the ecological corridors they lay within, or even restore ecological functionality to those that have lost it as a result of roads' fragmenting effects. Additionally, we recommend installing wildlife fencing along our study area, with sections that end at the entrances to drainage culverts, and that culvert entrances be situated on the habitat-side (rather than the highway-side) of the fence (Ford & Clevenger 2019). This is in accordance with Rytwinski et al.'s (2016) meta-analysis that found animal mortality on roads most significantly decreases when wildlife passages are employed in combination with wildlife fencing. In lieu of designated crossing structures, ending fence sections at culvert entrances would be the best possible strategy in the current situation. Lastly, larger wildlife passages should be considered to facilitate the movement of larger mammals.

THESIS CONCLUSION

In this thesis we have assessed the factors affecting mammals' entry and full crossing of drainage culverts while employing several novel data collection methods and statistical techniques. This is the first research project that has (1) used a periodically rotating motion-sensing camera structure to minimize detection bias present in individual cameras, (2) utilized both outward- and inward-facing cameras to determine outside presence of animals as well as inside of drainage culverts, (3) combined animal track data with motion-sensing camera data to assess the relationship between mammals present in the habitat adjacent to the road versus animals within detection-range of the trail cameras, and finally (4) utilized zero-inflated negative binomial generalized linear mixed effects models to test for the presence of structural zeros in a road-related wildlife study. All of these innovations have improved the strength of this study, and should be used in similar studies, either independently or used in combination with each other.

Roads have negative effects on wildlife, and autoroute 10 in southern Quebec is no exception. In this study, we sought to measure animal activity in proximity to, as well as inside of 13 drainage culverts underneath the road surface to answer three research questions: (1) what factors affect the rate of full passages by mammals through drainage culverts? How often? Which species fully cross? And for animals that are first detected outside of the drainage culverts, what factors affect their (2) entry, and (3) subsequent full passage of the drainage culverts? These research questions were answered using data collected from motion-sensing trail cameras, as well as track boxes, designed to collect the tracks of mammals using a scent lure and ink.

We found that (1) the presence of tracks of a species in the habitat adjacent to a culvert is highly correlated with that species fully crossing the culvert, that temperature is positively correlated with the rate of full passages, and that water level is such a strong deterrent to animals in our study area that excess zeros were generated in the statistical models. Additionally, (2) the construction material of drainage culverts plays an important role in whether or not an animal will enter a culvert. Specifically, polyethylene was found to negatively affect animals' entry. The distance measured from a culvert's entrance to the forest edge was found to positively affect animal entry into culverts, as was the luminosity of the moon. Water level was found to negatively impact entry. Lastly, (3) no variables were found to significantly affect an animal's full passage of a drainage culvert once it had already entered.

All of these results are highly valuable, and can be used to shape future decisions in the construction, alteration, and policy surrounding animal-friendly drainage culverts. In particular, I recommend that whenever possible, dry-ledges be installed in drainage culverts as this allows for animals exhibiting an avoidance to water to still safely cross under the road surface. Additionally, polyethylene should be avoided as a construction material to better encourage their use by animals. Lastly, because the intended purpose of the drainage culvert is to allow for the passage of water, and because mammal entry into culverts was found to be negatively correlated with water level, the drainage culvert is not an adequate substitute for designated crossing structures for mammals. Whenever possible, dry culverts or otherwise wildlife-centered crossing structures should be installed wherever possible to allow for the safe passage of mammals under or over roads, and to alleviate some of the negative effects that habitat fragmentation is having on wildlife in Quebec, Canada, and the world.

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APPENDIX A

A.1 Objectives

The goal of the project was to monitor animal activity along Quebec's autoroute 10 at two scales: under the road (drainage culverts), and at a short distance from the road (track data). Animal activity in and around drainage culverts was recorded using motion-sensing trail cameras (Reconyx™ HC600 Hyperfire H.D. Covert IR). Track data was collected using track boxes developed and constructed in-house following the design developed by Katrina Bélanger-Smith (2014).

A.2 Study area

The study area was along Quebec's autoroute 10, between kilometre markers 82 and 114.6 and included the road surface, bank, ditch, and habitat surrounding the road up to a distance of 40 metres. The portion of autoroute 10 encompassing the study area received on average 30,950 vehicles per day in 2017 according to data from the Quebec Ministry of Transport.

Tab. A.1: Location of drainage culvert sites.

Site	Ministry site name	Highway	Location
M6	170879	10	45°18'08.7"N 72°26'08.0"W
M7	237988	10	45°18'12.0"N 72°24'37.2"W
2	237987	10	45°18'06.8"N 72°24'04.7"W
3	0076-0	10	45°18'07.8"N 72°23'18.6"W
4	0077-0	10	45°18'07.9"N 72°23'06.9"W
8	0081-0	10	45°18'21.0"N 72°21'03.7"W
11	0085-0	10	45°17'55.0"N 72°19'08.3"W
14	0088-0	10	45°17'45.4"N 72°17'49.3"W
15	0089-0	10	45°17'44.3"N 72°17'38.5"W
17	0099-0	10	45°17'22.7"N 72°15'04.0"W
21	0103-0	10	45°17'31.5"N 72°13'26.8"W
22	0104-0	10	45°17'31.9"N 72°13'20.8"W
28	P-09815	10	45°17'33.6"N 72°12'20.6"W

A.3 Safety

Because our work took place in a constantly potentially hazardous environment, caution was taken at all times to ensure that both fieldwork crew and motorists were safe. High visibility safety vests were worn by the fieldwork crew at all times, as well as hard hats while on the road surface. Our research vehicle was equipped with a flashing orange beacon light as well as a large orange traffic arrow, signaling to motorists to pass with caution. To access the drainage culvert sites underneath the road, the research vehicle had to be parked at the side of the road. To minimize danger, parking only took place where a guard rail was not present, allowing the research vehicle to maximize its distance from the road surface. Additionally, fieldwork crew members only travelled in groups of two or more, minimizing the risk of an accident in the field going unnoticed. Appropriate clothing was worn at all times during fieldwork, including closed-toe shoes and waterproof pants.

A.4 Permits

Two permits were provided by the Quebec Ministry of Transport:

1. Permit to install and collect data from trail cameras inside of drainage culverts (PV 9008-80-45093-17003).
2. Permit to install and collect data from animal footprint-collecting track boxes in the surrounding habitat (PV 9008-80-45093-17003).

A.5 Weather Standards

Camera rotations took place in all types of weather conditions (camera data collection took place from June 5th, 2019 to December 4th, 2019). During the winter months, notice of fieldwork was given to the Quebec Ministry of Transport several days before the expected fieldwork date. If weather conditions were forecasted to be blizzarding or other highly unfavorable conditions, fieldwork was postponed to the next day with more favorable weather. Track box field days only took place during the summer and fall months (from June 6th, 2019 to November 9th, 2019). The only weather prohibiting fieldwork were thunderstorms. If lightning was observed or forecasted, fieldwork was postponed to the next day with more favorable weather.

A.6 Time of day standards

Fieldwork days usually ran from 8 am to 5 pm during the summer months. Camera rotation days taking place in the winter were usually completed between the hours of 9am and 4pm.

A.7 Field Procedure for Camera Installation and Rotation

1. Four cameras were installed inside of each drainage culvert. Each entrance housed one inward- and one outward-facing camera (Fig. A.1). Camera security boxes were installed into the top of the structure. For steel and polyethylene culverts, an additional hole was drilled through the top of the structure to secure a padlock attached to a security wire, deterring theft. Because this was not possible with concrete culverts, simply securing the camera security box using concrete screws proved to be sufficient (Tab. A.1, Fig. A.2). A preliminary study using metal poles inserted into the ground in front of the drainage culverts was attempted, but proved to be ineffective compared to mounting the cameras on the drainage culverts themselves. This did not work because the ground was too soft. Mounting the poles in a concrete base has been used in past studies (Quebec Ministry of Transportation, unpublished data) and has shown to be very effective, but did not fit into the budget of this project.

Fig. A.1: a two-camera setup was employed within each culvert.

Tab. A.2: Trail camera security box installation part-list.

Steel and poly culverts		Concrete culverts	
Quantity	Item	Quantity	Item
1	L-bracket	1	L-bracket
2	2” carriage bolt	2	2” carriage bolt
2	½” carriage bolt	2	½” carriage bolt
4	Washer	4	Washer
4	Nut	4	Nut
1	Security wire	1	Lock
2	Lock		

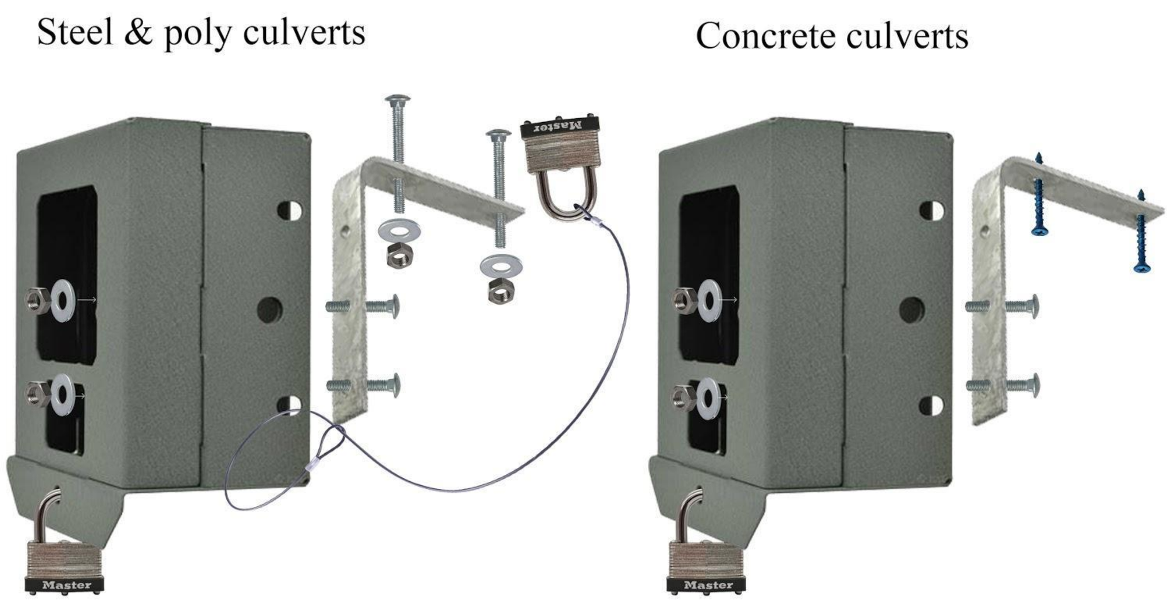


Fig. A.2: Installation schematic for steel and polyethylene culverts (left) and concrete culverts (right).

2. To minimize the potential of camera detection bias influencing results, a rotation of cameras was performed on a set schedule. Collecting data on half of the study area’s drainage culverts per two-week session, cameras were rotated in a counter-clockwise fashion, ensuring that a different combination of cameras were used to collect data at each site every session (Fig. A.3). This stems from personal observation and studies indicating that individual trail cameras within and between models and companies

can vary significantly (Meek et al. 2014, Jumeau et al. 2017). By rotating cameras we normalized any trigger delays and other potential differences that may have occurred among individual cameras. Camera rotations were executed every 14 days, except for one rotation in November of 2018 which was delayed by one day. The extra day of data was deleted, and rotations days were moved one day later for all future rotations to maintain the 14 day schedule.

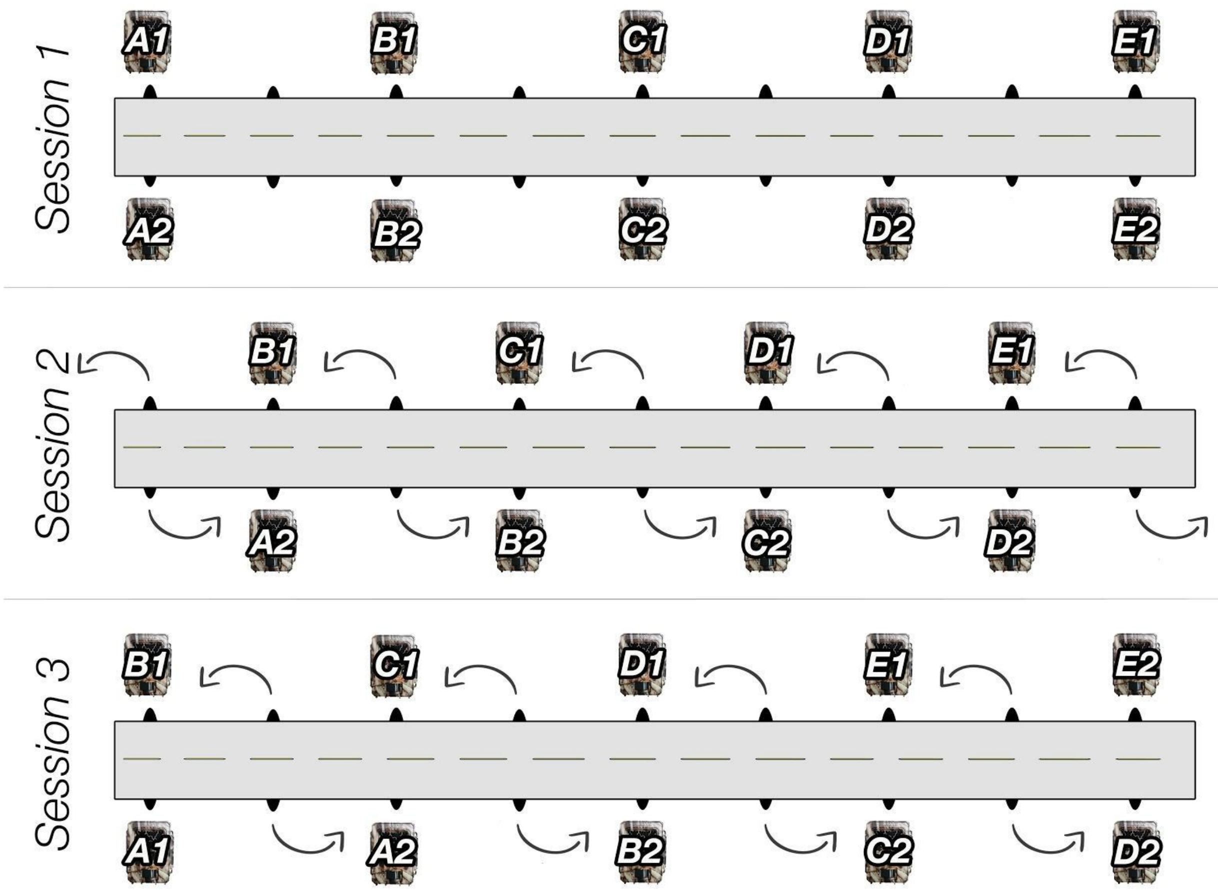


Fig. A.3: Illustration of the camera rotation schedule (3 two-week sessions shown).

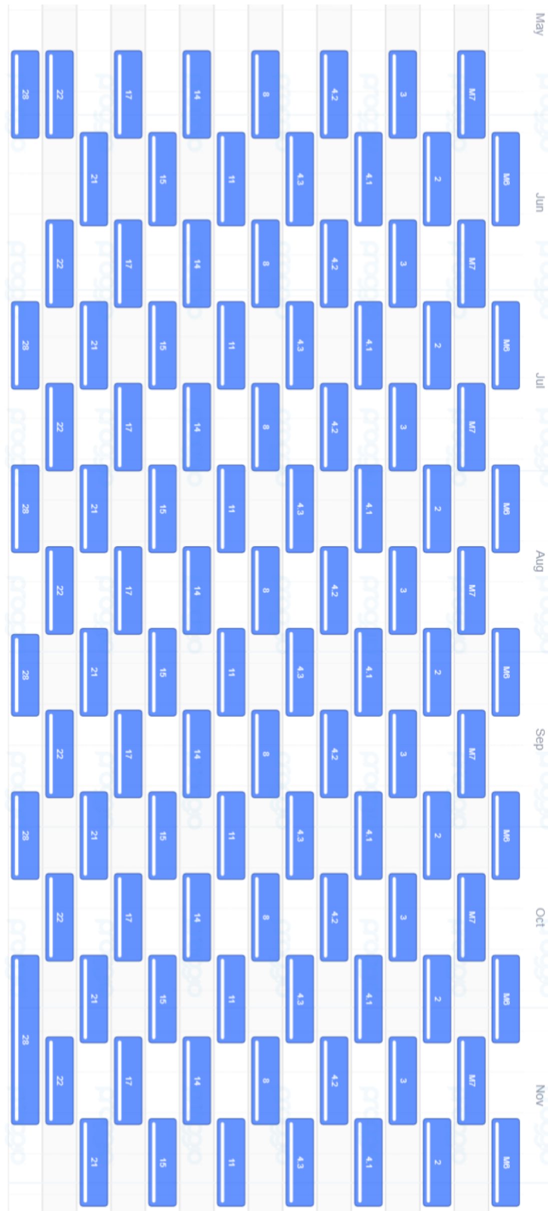


Fig. A.4: Temporal layout of camera rotation. Blue blocks mark times when cameras are active in each site.

3. Batteries (Energizer L91 Ultimate Lithium AA 3000mAh 1.5V) were checked and replaced as needed every two weeks, and site-labelled SD cards were switched before being placed in new sites. Paying close attention to the SD card labels, the used cards were placed in a secure ziplock bag, while fresh cards were inserted into the camera to be deployed at the next site. Batteries reading under 40% charge (as indicated by the camera) were replaced with new batteries. The old batteries were brought back to the lab to be

individually tested using a ZTS battery tester (testing in % increments of 20). Batteries at or over 60% charge were collected for future use, while batteries under 60% were properly disposed of.

4. After all of the SD cards were collected, they were brought back to the lab where the photos were copied onto hard drives and backup drives for later data input.

A.8 Photo storage and analysis procedure

1. Photos were organized according to site name. Within each site, folder a series of “sampling period folders” were made, containing the photos collected during each two-week collection session. These session folders were named according to the dates that the cameras were deployed at that site (for example, “01-01-2018 to 14-01-2018”). Within each session folder were four “camera” folders: “north in”, “north out”, “south in”, and “south out”. Each of these folders contain the photos collected by the corresponding camera at that site during the session period.

2. A google sheets file was created to store the photo ID data. While looking closely at each visit to the drainage culvert by a mammal, information about that visit was recorded, one visit per spreadsheet row. Spreadsheet columns include: “site name”, “camera name”, “water level (cm)”, “species”, “number of individuals detected”, “direction of travel”, “date”, “time”, “temperature”, “moon phase”, “behavior” (for outward facing camera detections), “photo ID”, and four columns that binomially record the outcome of the mammal’s visit to the drainage culvert: “full crossing”, “exploration”, “unknown”, and “outside”. If the animal is observed fully crossing the drainage culvert, a “1” is placed in the “full passage” column, with zeros placed in the “exploration”, “unknown”, and “outside” columns.

3. For each detection per camera, the clearest image recorded of the mammal was copied into a separate folder titled “reference photos”. These image files were organized into folders separated by site, with the

image file names indicating the site, species, and date of detection. For example, “2.fox.14.1.2018”. This file name was then copied and pasted into the spreadsheet’s “photo ID” column. This allows for a much easier and faster secondary photo ID validation process, without having to navigate through the entire photo collection again.

site	Ministry site	Corridor	Material	Camera	Length (	Width (cm	Height (cr	Str. Open	Water	Species	#	Direction	Date	Time	Temp	Moon	Full	Exp	Unkn	Out beha	Photo ID	Notes
M6	170879	1	steel	S in	13040	180	180	2.48	1	mink	1	N	2018-11-22	11:18:52	-13	FM	1	0	0		M6.mink.2018.11.22	
M6	170879	1	steel	S in	13040	180	180	2.48	1	mink	1	S	2018-11-22	14:20:16	-4	FM	1	0	0		M6.mink.2018.11.22 (2)	
M6	170879	1	steel	S in	13040	180	180	2.48	1	mink	1	S	2018-11-25	14:20:16	-4	FM	1	0	0		M6.mink.2018.11.22 (2)	
M6	170879	1	steel	S in	13040	180	180	2.48	1	mink	1	S	2018-11-25	10:32:33	1	Wan G	1	0	0		M6.mink.2018.11.25	
M6	170879	1	steel	S in	13040	170	170	2.22	5	muskrat	1	N	2018-07-08	11:43:32	24	Wan C	1	0	0		M6.Muskrat.2018.07.08	
M6	170879	1	steel	S in	13040	170	170	2.22	9	muskrat	1	N	2018-09-09	14:44:51	21	NM	1	0	0		M6.muskrat.2018.09.09	
M6	170879	1	steel	S in	13040	170	170	2.22	16	muskrat	1	S	2018-03-03	18:29:20	1	FM	1	0	0		M6.Muskrat.2018.03.03	
M6	170879	1	steel	S in	13040	170	170	2.22	15	muskrat	1	S	2018-03-08	18:18:01	0	LQ	1	0	0		M6.Muskrat.2018.03.08	
M6	170879	1	steel	S in	13040	170	170	2.22	12	muskrat	1	S	2018-03-13	3:02:30	0	Wan C	1	0	0		M6.Muskrat.2018.03.13	
M6	170879	1	steel	S in	13040	170	170	2.22	8	muskrat	1	S	2018-03-14	2:46:55	0	Wan C	1	0	0		M6.Muskrat.2018.03.14	
M6	170879	1	steel	S in	13040	170	170	2.22	8	muskrat	1	S	2018-03-31	19:09:37	2	FM	1	0	0		M6.Muskrat.2018.03.31	
M6	170879	1	steel	S in	13040	170	170	2.22	7	muskrat	1	S	2018-04-03	17:58:22	5	Wan G	1	0	0		M6.Muskrat.2018.04.03	
M6	170879	1	steel	S in	13040	170	170	2.22	11	muskrat	1	N	2018-04-06	19:39:03	0	LQ	1	0	0		M6.Muskrat.2018.04.06	
M6	170879	1	steel	S in	13040	170	170	2.22	15	muskrat	1	N	2018-04-25	10:29:31	7	Wax C	1	0	0		M6.Muskrat.2018.04.25	
M6	170879	1	steel	S in	13040	170	170	2.22	10	muskrat	1	N	2018-05-01	13:04:30	11	FM	1	0	0		M6.Muskrat.2018.05.01	
M6	170879	1	steel	S in	13040	170	170	2.22	10	muskrat	1	N	2018-05-07	10:42:57	11	LQ	1	0	0		M6.Muskrat.2018.05.07	
M6	170879	1	steel	N in	13040	180	180	2.48	0	otter	2	N	2018-01-08	20:49:10	-2	LQ	1	0	0		M6.Otters.2018.01.08	
M6	170879	1	steel	S in	13040	170	170	2.22	8	raccoon	1	N	2018-03-27	18:06:27	5	Wax G	0	1	0		M6.Raccoon.2018.03.27	
M6	170879	1	steel	S in	13040	170	170	2.22	8	raccoon	2	N	2018-03-28	6:01:13	0	Wax G	0	1	0		M6.Raccoon.2018.03.28	
M6	170879	1	steel	S out	13040	170	170	2.22	22	raccoon	1	E	2018-06-08	10:54:40	19	Wan C	0	0	0	Pass	M6.Raccoon.2018.06.08	
M6	170879	1	steel	S out	13040	170	170	2.22	22	raccoon	1	E	2018-06-08	15:11:23	29	Wan C	0	0	0	Pass	M6.Raccoon.2018.06.08 (2)	
M6	170879	1	steel	S out	13040	170	170	2.22	22	raccoon	1	E	2018-06-09	11:12:10	20	Wan C	0	0	0	Pass	M6.Raccoon.2018.06.09	
M6	170879	1	steel	S out	13040	170	170	2.22	22	raccoon	1	W	2018-06-16	10:28:23	21	Wax C	0	0	0	Pass	M6.Raccoon.2018.06.16	
M6	170879	1	steel	S out	13040	170	170	2.22	8	raccoon	1	N	2018-05-14	12:21:05	24	NM	1	0	0	Enter	M6.Raccoon.2018.05.14	
M6	170879	1	steel	S out	13040	170	170	2.22	8	raccoon	1	S	2018-05-14	14:16:38	29	NM	1	0	0	Exit	M6.Raccoon.2018.05.14 (2)	
M6	170879	1	steel	N in	13040	180	180	2.48	0	unkn	1	S	2018-01-18	13:56:16	-1	NM	0	0	1		M6.UNKN.2018.01.18	
M7	237988	1	poly	S out	5000	105	105	2.21	35	bear	1	E	2018-05-21	22:41:41	12	FQ	0	0	0	Pass	M7.Bear.2018.05.21	
M7	237988	1	poly	S out	5000	105	105	2.21	35	deer	1	W	2018-05-22	7:48:25	13	FQ	0	0	0	Pass	M7.Deer.2018.05.22	
M7	237988	1	poly	S out	5000	105	105	2.21	35	deer	1	W	2018-05-22	7:50:17	13	FQ	0	0	0	Pass	M7.Deer.2018.05.22 (2)	
M7	237988	1	poly	S out	5000	105	105	2.21	35	deer	3	W	2018-05-22	8:48:16	17	FQ	0	0	0	Pass	M7.Deer.2018.05.22 (3)	
M7	237988	1	poly	S out	5000	105	105	2.21	35	deer	2	W	2018-05-23	19:12:56	21	FQ	0	0	0	Pass	M7.Deer.2018.05.23	
M7	237988	1	poly	S out	5000	105	105	2.21	35	deer	1	W	2018-05-30	20:05:10	25	FM	0	0	0	Pass	M7.Deer.2018.05.30	
M7	237988	1	poly	S out	5000	105	105	2.21	35	deer	1	E	2018-06-02	6:06:58	13	Wan G	0	0	0	Pass	M7.Deer.2018.06.02	
M7	237988	1	poly	S out	5000	105	105	2.21	42	deer	1	W	2018-06-19	13:42:09	30	FQ	0	0	0	pass	M7.deer.20	end of session 5

Tab. A.3: Example of the raw data spreadsheet.

4. After this process was completed, secondary “site specific” data was added to the spreadsheet. New columns were added: “structure material” (concrete, polyethylene, or steel), “structure length (cm)”, “structure width (cm)”, structure height (cm)”, “distance from the culvert entrance to the nearest habitat edge (m)”, and “structure openness” (W*H/L).

5. Because the raw data has one row per detection of a visit per camera, a mammal that crosses fully from one end of a drainage culvert to the other would ideally trigger all four cameras, resulting in four rows of data per mammal visit. To clean the data to make one row per visit, a new tab titled “full crossing validation” in the spreadsheet was created, copying all of the raw data to it.

6. The data in this new tab was then organized according to site, and then further organized according to date. Data for every day per site is then organized according to the time of day that the visit was recorded. This allows the data analyst to easily see which cameras were triggered for each mammal visit.

Site	Corridor	Material	Camera	Length	Width	Height	Str. Open	Species	Date	Time	Water (cm)	Temp	Full	Exp	Unkn	Out	Cam	QMoon
2	0	steel	N out	6250	120	120	2.30	bobcat	2018-06-10	1:42:29	7	10	0	0	0	1		.25
2	0	steel	S out	6250	120	120	2.30	deer	2018-06-17	10:23:04	13	21	0	0	0	1		.25
2	0	steel	N out	6250	120	120	2.30	rabbit	2018-06-17	19:09:26	7	23	0	0	0	1		.25
2	0	steel	S out	6250	120	120	2.30	deer	2018-06-18	8:23:26	13	16	0	0	0	1		.25
2	0	steel	S in	6250	120	120	2.30	mink	2018-07-09	8:54:23	2	16	0	0	1	0		.25
2	0	steel	S in	6250	120	120	2.30	mink	2018-07-13	20:30:25	2	18	0	0	1	0		0
2	0	steel	N out	6250	120	120	2.30	deer	2018-07-16	12:53:23	5	29	0	0	0	1		.25
2	0	steel	N out	6250	120	120	2.30	deer	2018-07-16	22:05:51	5	18	0	0	0	1		.25
2	0	steel	S out	6250	120	120	2.30	bear	2018-08-03	4:02:32	2	19	0	0	0	1		.50
2	0	steel	N in	6250	120	120	2.30	mink	2018-08-06	15:45:34	1	23	0	0	1	0		.25
2	0	steel	S in	6250	120	120	2.30	mink	2018-08-06	16:16:34	2	26	0	0	1	0		.25
2	0	steel	N in	6250	120	120	2.30	mink	2018-08-06	16:58:17	1	22	0	0	1	0		.25
2	0	steel	N in	6250	120	120	2.30	mink	2018-08-13	10:03:52	1	20	0	0	1	0		.25
2	0	steel	S in	6250	120	120	2.30	mink	2018-08-31	1:54:08	5	14	0	0	1	0		.75
2	0	steel	S in	6250	120	120	2.30	mink	2018-09-01	9:43:39	5	15	1	0	0	0	in in	.50
2	0	steel	S in	6250	120	120	2.30	mink	2018-09-02	12:09:06	5	18	1	0	0	0	in in	.50
2	0	steel	S in	6250	120	120	2.30	mink	2018-09-07	2:16:57	5	15	0	0	1	0		.25
2	0	steel	N out	6250	120	120	2.30	mink	2018-09-08	4:27:23	4	15	0	0	0	1		0
2	0	steel	N out	6250	120	120	2.30	mouse	2018-09-08	20:27:28	4	13	0	0	0	1		0
2	0	steel	S in	6250	120	120	2.30	mink	2018-09-09	20:57:49	5	11	1	0	0	0	in in	0
2	0	steel	S out	6250	120	120	2.30	mink	2018-10-08	19:49:03	2	10	0	0	1	0		0

Tab. A.4: Example of confirmed full-crossing spreadsheet.

7. To confirm a full crossing, an animal must be detected travelling in the same direction, entering one side of the drainage culvert and exiting the other side, by at least two cameras, and at both ends of the drainage culvert. Accordingly, a full crossing can be confirmed if a mammal is detected by all four cameras, both inward-facing cameras, one inward- and one outward-facing camera, or both outward-facing cameras. The combinations of camera detections used to confirm each full passage are noted in

Fig. A.5. Unknowns from this dataset were excluded from statistical analysis.

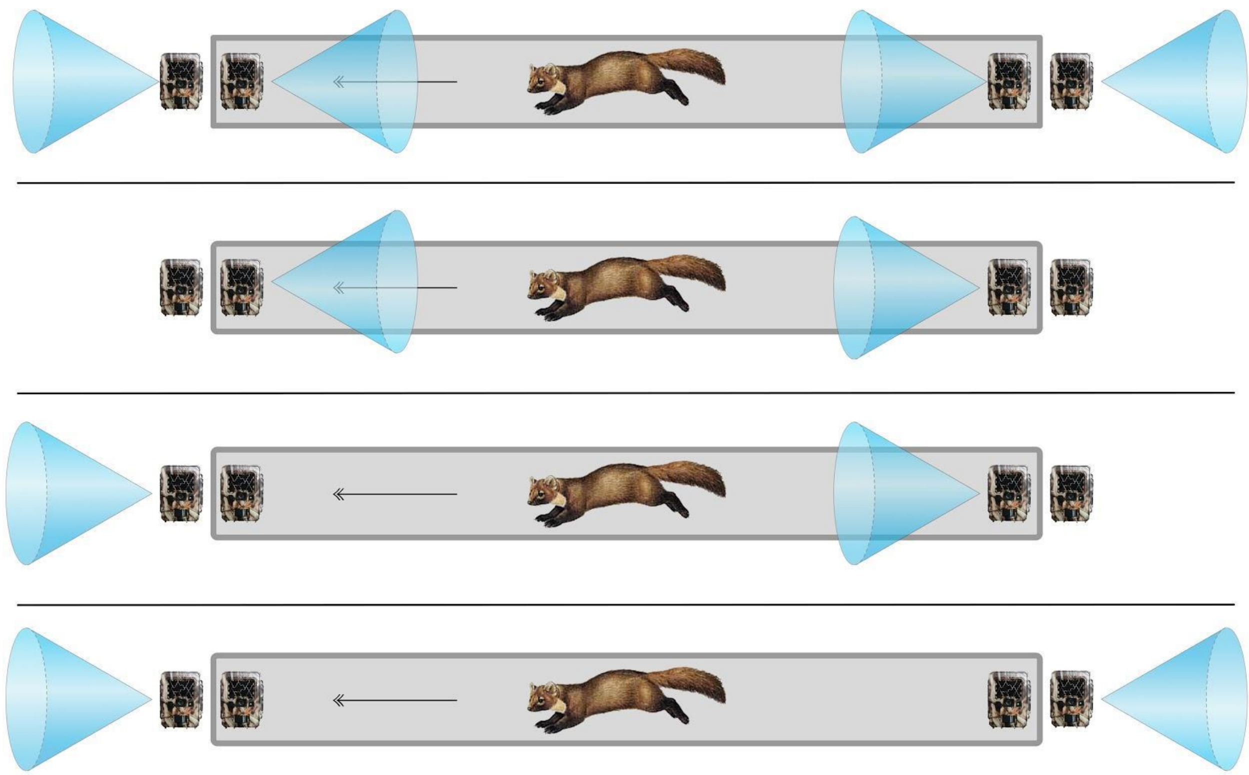


Fig. A.5: Illustration of camera triggers that were used to confirm a full passage.

8. To convert the above-mentioned dataset to a count dataset for ZINB GLMM regression analysis, a new spreadsheet was created. Using formulae to reference between the new sheet and the sheet containing the raw validated full crossing data, counts of full crossings, explorations, unknowns, and outside detections were created for each species per site per two-week sampling period. Unknowns were excluded from statistical analysis.

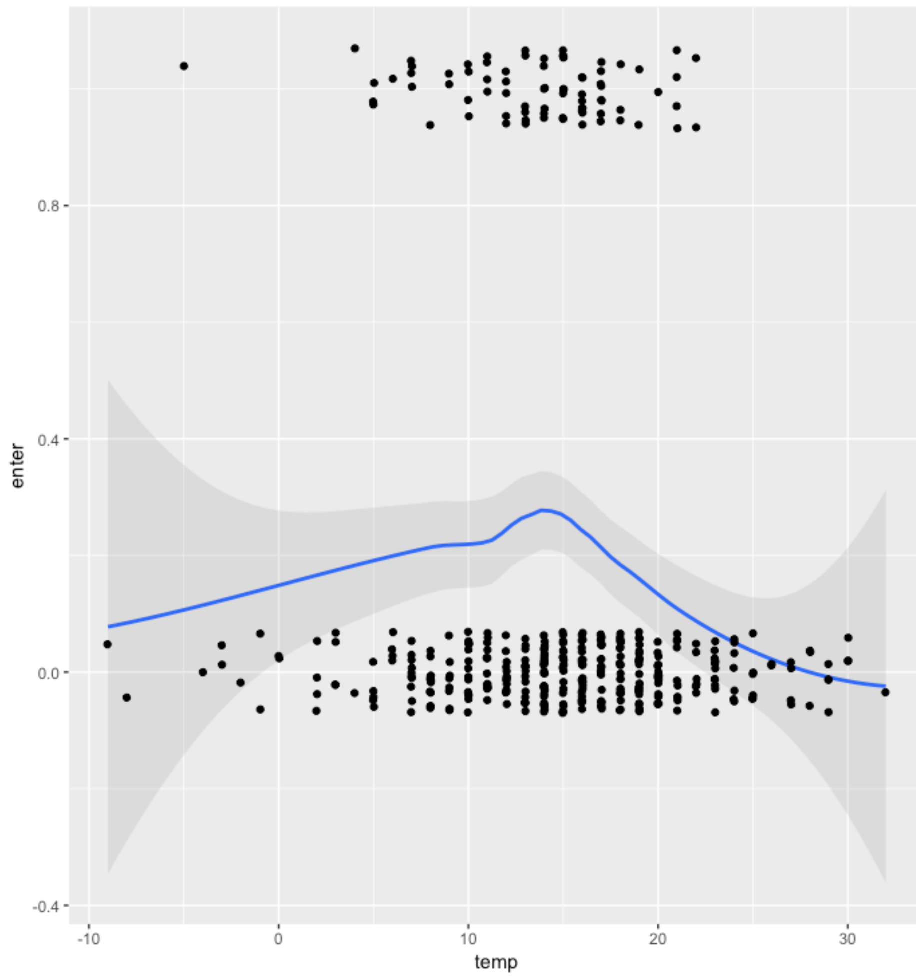
A.9 Transformation of the temperature variable

For our logistic regression analysis answering research question two, a clear peak in animal entries into drainage culverts was observed at approximately 14°C. To try and make any statistical relationships more visible, we therefore attempted to transform the temperature variable for this dataset:

$$\Delta temp = 14 - temp$$

to reflect each datapoint's absolute difference from the peak temperature (Fig. A.6). However, using this variable for only research question 2, compounded with its elimination from the final model led to our discarding of its use in this thesis. Instead, non-transformed temperature (°C) was used in all models.

a)



b)

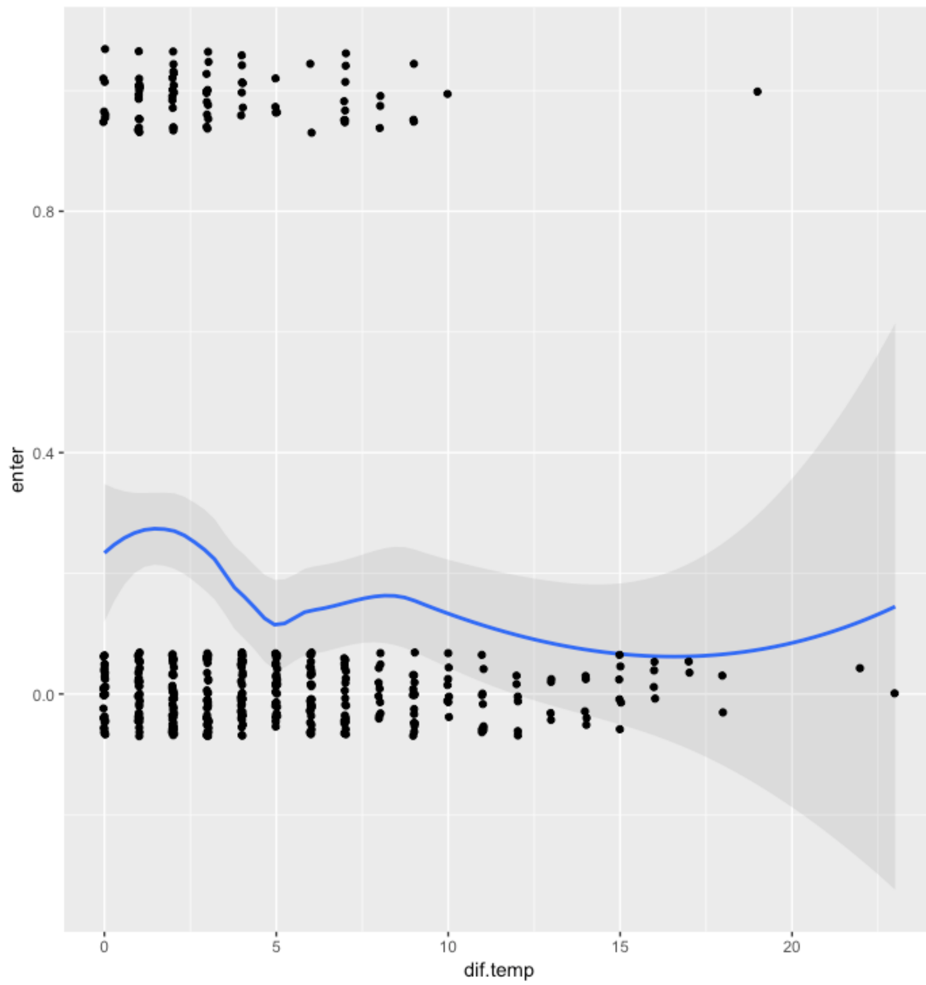


Fig. A.6: Initial plot of animal entries into drainage culverts by temperature (a), followed by the transformed temperature variable reflecting each point's absolute difference from 14 °C (b).

APPENDIX B:

Extended results

Tab. B.1: Total camera detections per species per site:

	Culvert	M6	M7	2	3	4	8	11	14	15	17	21	22	28	
Species	Raccoon	4	9	55	31	23	2	121	7	115	80	68	48	15	**578**
	Whitetail deer	12	6	4	38	32	10	22	36	11	9	2	2	9	**193**
	Am. mink	5	10	13	7	25	7	1	0	0	32	25	2	0	**127**
	Eastern squirrel	0	0	11	1	0	0	2	3	2	19	0	0	3	**41**
	Weasel spp.	0	1	4	1	0	0	0	0	1	6	15	4	0	**32**
	Muskrat	2	0	0	0	22	1	5	0	1	0	0	0	0	**31**
	Unknown	0	2	1	1	5	2	3	0	2	4	5	1	1	**27**
	Red fox	0	0	0	0	0	1	4	0	19	0	1	0	0	**25**
	Woodchuck	0	0	6	0	0	1	1	4	2	8	0	0	2	**24**
	Mouse spp.	0	1	1	0	1	0	0	0	7	9	5	1	0	**25**
	Eastern chipmunk	0	0	0	0	0	0	0	0	1	5	1	0	0	**7**
	Snowshoe Hare	0	2	3	0	0	0	0	0	0	0	0	0	0	**5**
	N. Am. river otter	0	0	0	0	3	0	0	0	0	1	0	0	0	**4**
	Black bear	0	1	1	1	0	0	0	0	0	0	0	0	0	**3**
	Bobcat	1	0	1	0	1	0	0	0	0	0	0	0	0	**3**
	N. Am. porcupine	0	0	0	1	1	0	0	0	0	0	0	0	0	**2**
	Coyote	0	0	0	0	0	0	0	0	0	0	1	0	0	**1**
	Striped skunk	0	0	0	0	0	0	0	1	0	0	0	0	0	**1**
	N. Am. beaver	1	0	0	0	0	0	0	0	0	0	0	0	0	**1**
Sum	total	**25**	32	100	81	113	24	159	51	162	174	123	58	39	

Tab. B.2: Total full crossings per species per site:

	Culvert	M6	M7	2	3	4	8	11	14	15	17	21	22	28	
Species	Raccoon	0	3	29	12	0	0	53	1	22	37	39	19	2	**217**
	Whitetail deer	0	0	0	0	0	0	0	2	0	0	0	0	5	**7**
	Am. mink	0	0	3	0	1	0	0	0	0	7	6	0	0	**17**
	Eastern squirrel	0	0	0	0	0	0	0	0	0	1	0	0	0	**1**
	Weasel spp.	0	0	0	0	0	0	0	0	0	2	2	0	0	**4**
	Muskrat	0	0	0	0	1	0	0	0	0	0	0	0	0	**1**
	Unknown	0	0	0	0	0	0	0	0	1	0	0	0	0	**1**
	Red fox	0	0	0	0	0	0	0	0	2	0	0	0	0	**2**
	Woodchuck	0	0	0	0	0	0	0	1	1	0	0	0	0	**2**
	Mouse spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	Eastern chipmunk	0	0	0	0	0	0	0	0	0	1	0	0	0	**1**
	Snowshoe Hare	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	N. Am. river otter	0	0	0	0	0	0	0	0	0	1	0	0	0	**1**
	Black bear	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	Bobcat	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	N. Am. porcupine	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	Coyote	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	Striped skunk	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	N. Am. Beaver	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
Sum	total	**0**	3	32	12	2	0	53	4	26	49	47	19	7	

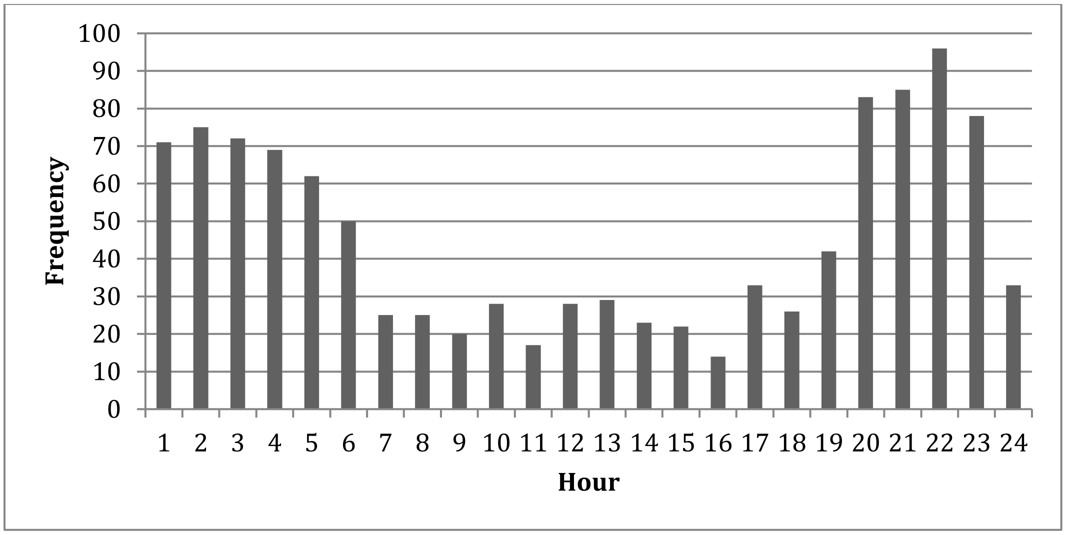
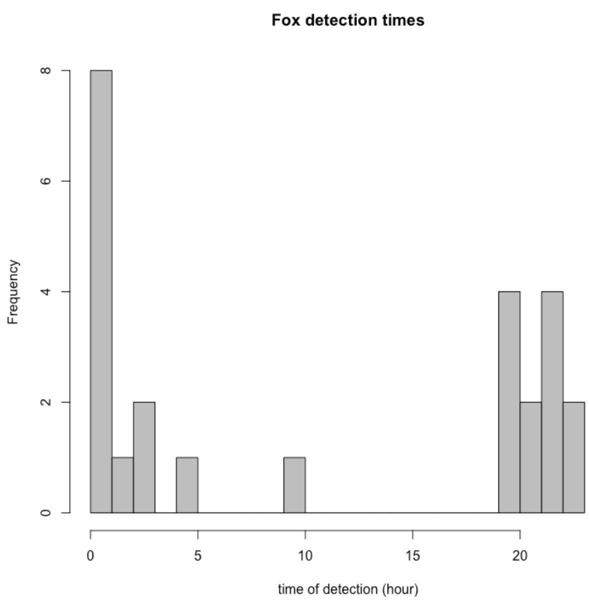
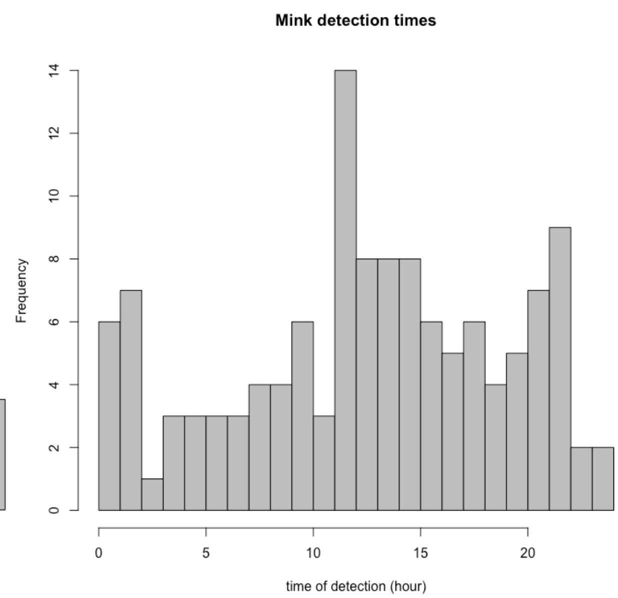
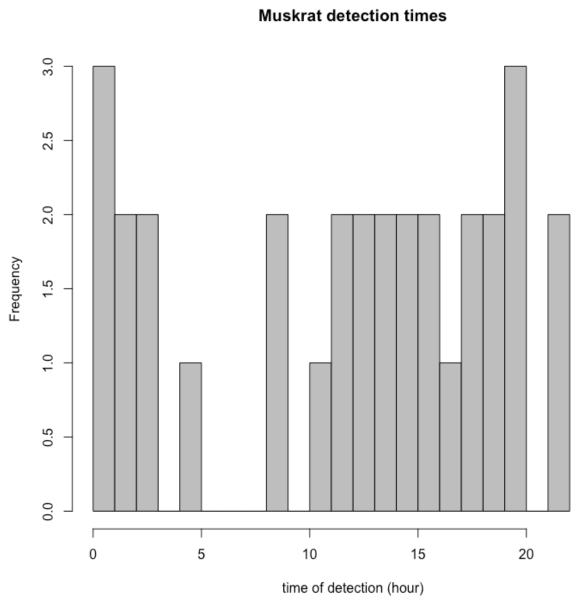
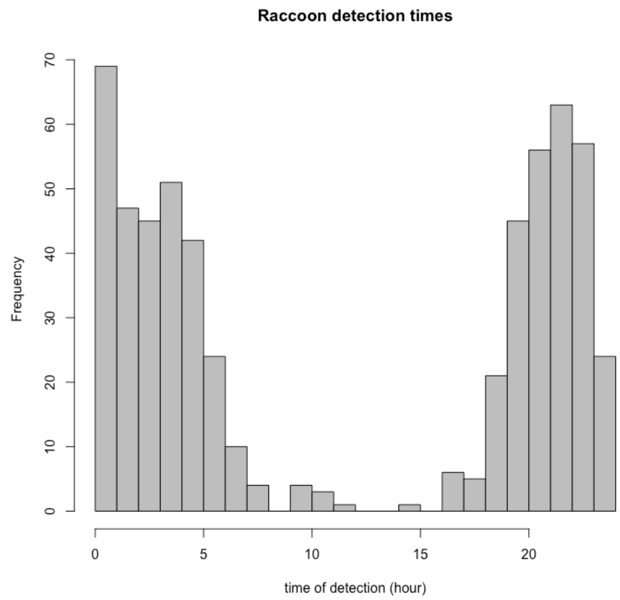


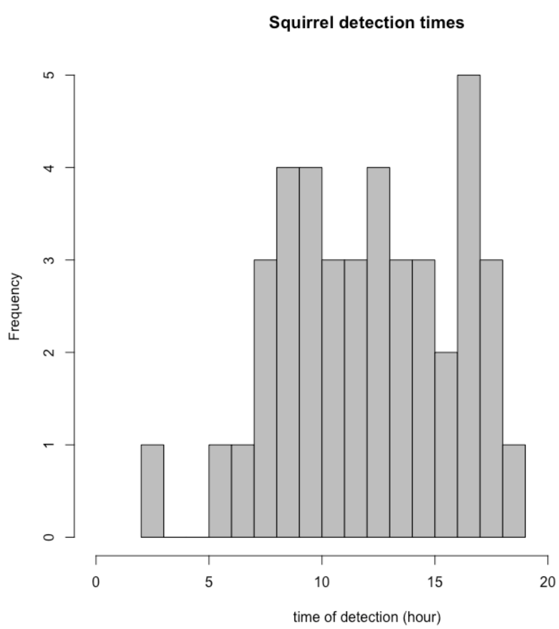
Figure B.1: Time of detection across all species.

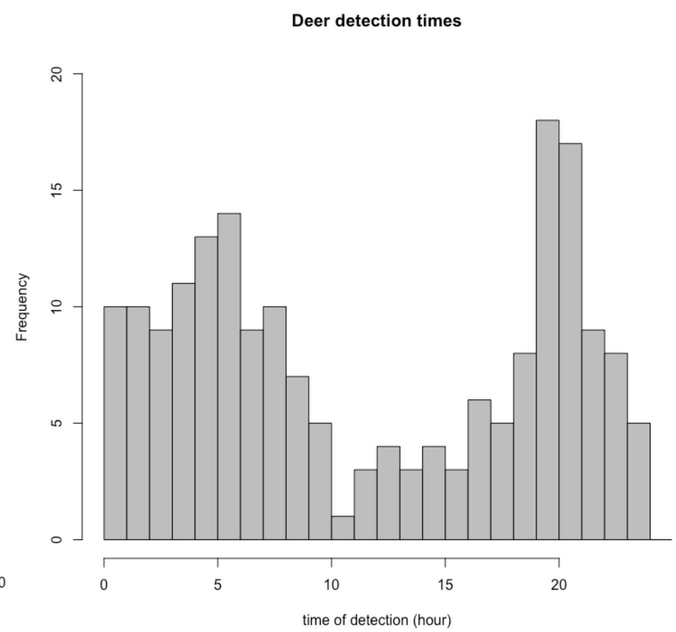


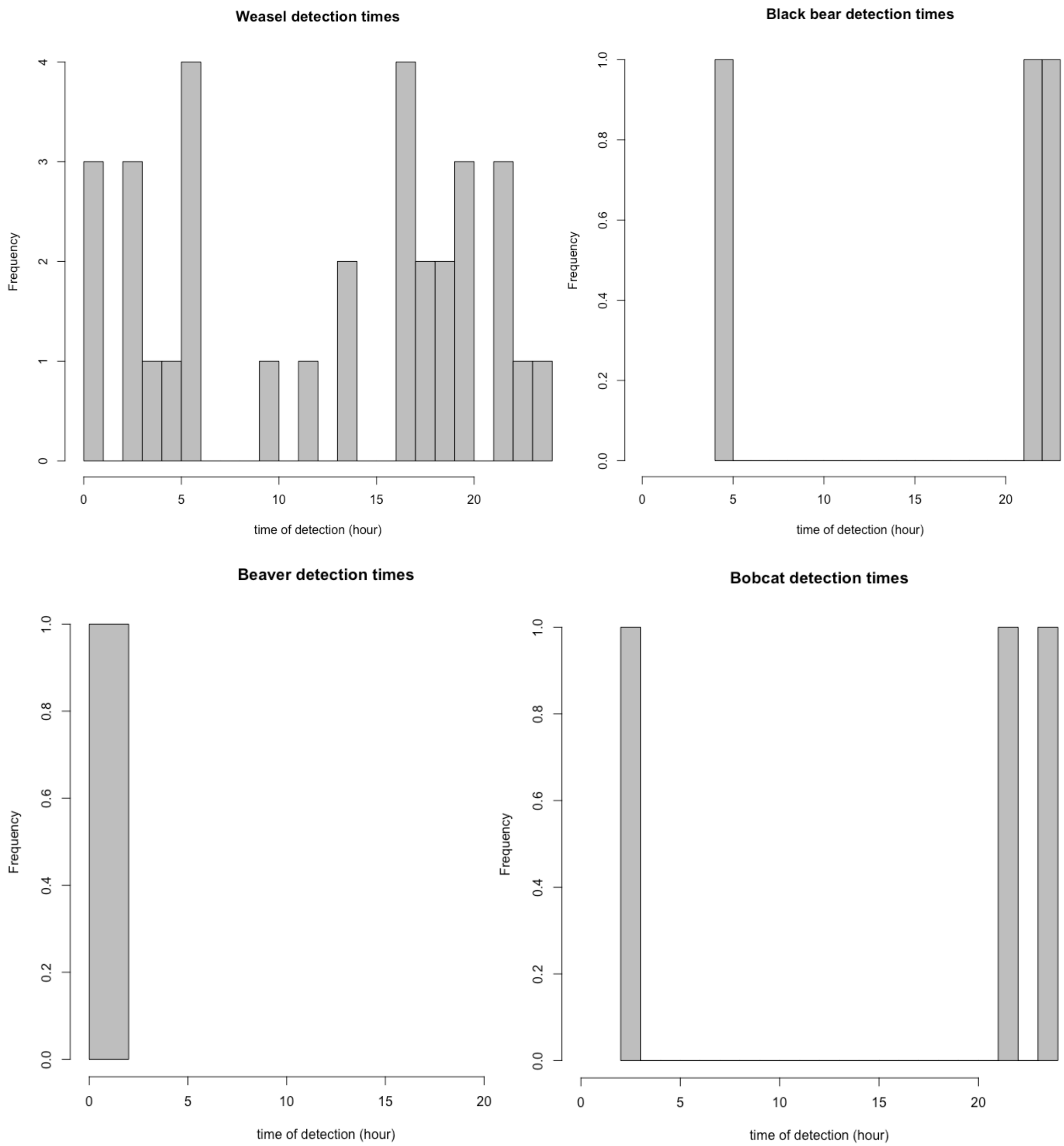


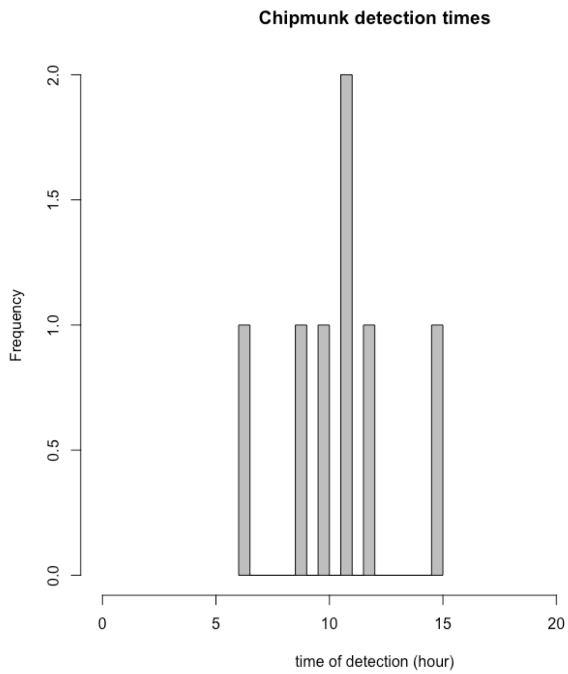

Muskrat detection times
Frequency
time of detection (hour)

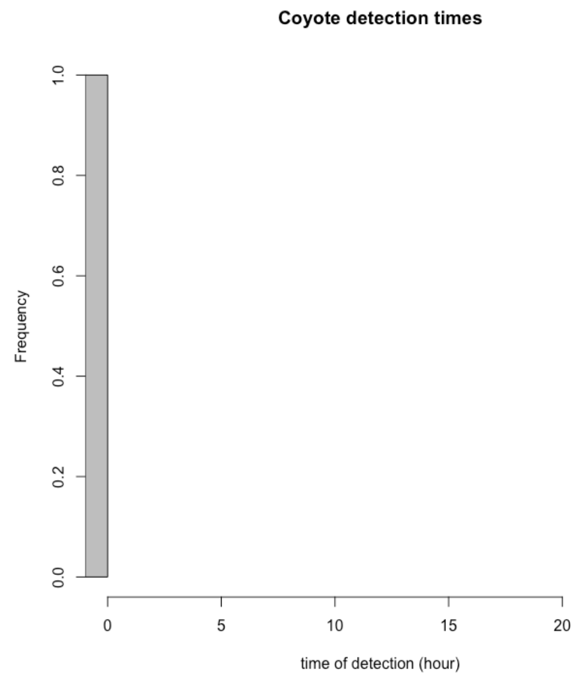

Raccoon detection times
Frequency
time of detection (hour)

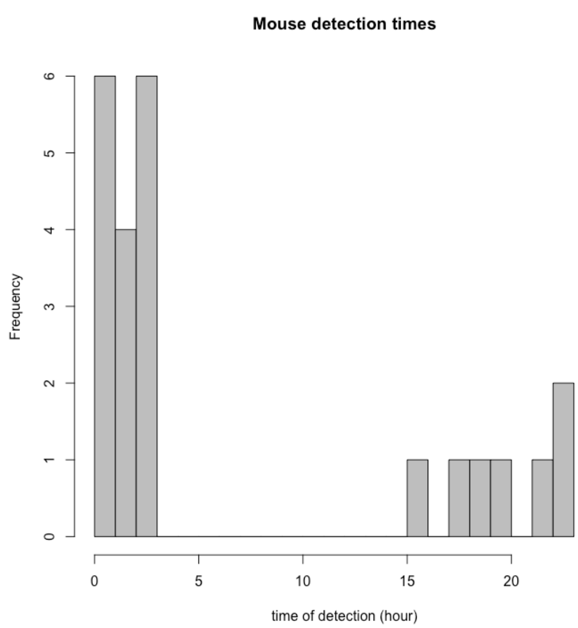

Squirrel detection times
Frequency
time of detection (hour)

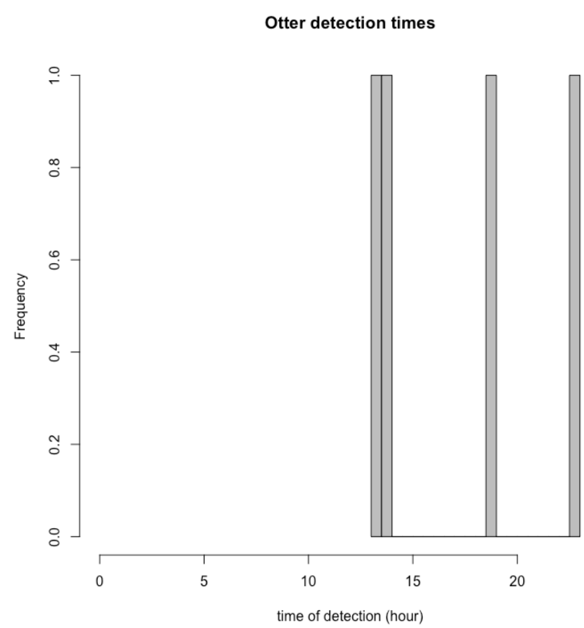

Deer detection times
Frequency
time of detection (hour)


Weasel detection times
Black bear detection times
Beaver detection times
Bobcat detection times
Frequency
time of detection (hour)


Chipmunk detection times
Frequency
0.0
0.5
1.0
1.5
2.0
0
5
10
15
20
time of detection (hour)


Coyote detection times
Frequency
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
time of detection (hour)


Mouse detection times
Frequency
0
1
2
3
4
5
6
0
5
10
15
20
time of detection (hour)


Otter detection times
Frequency
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
time of detection (hour)

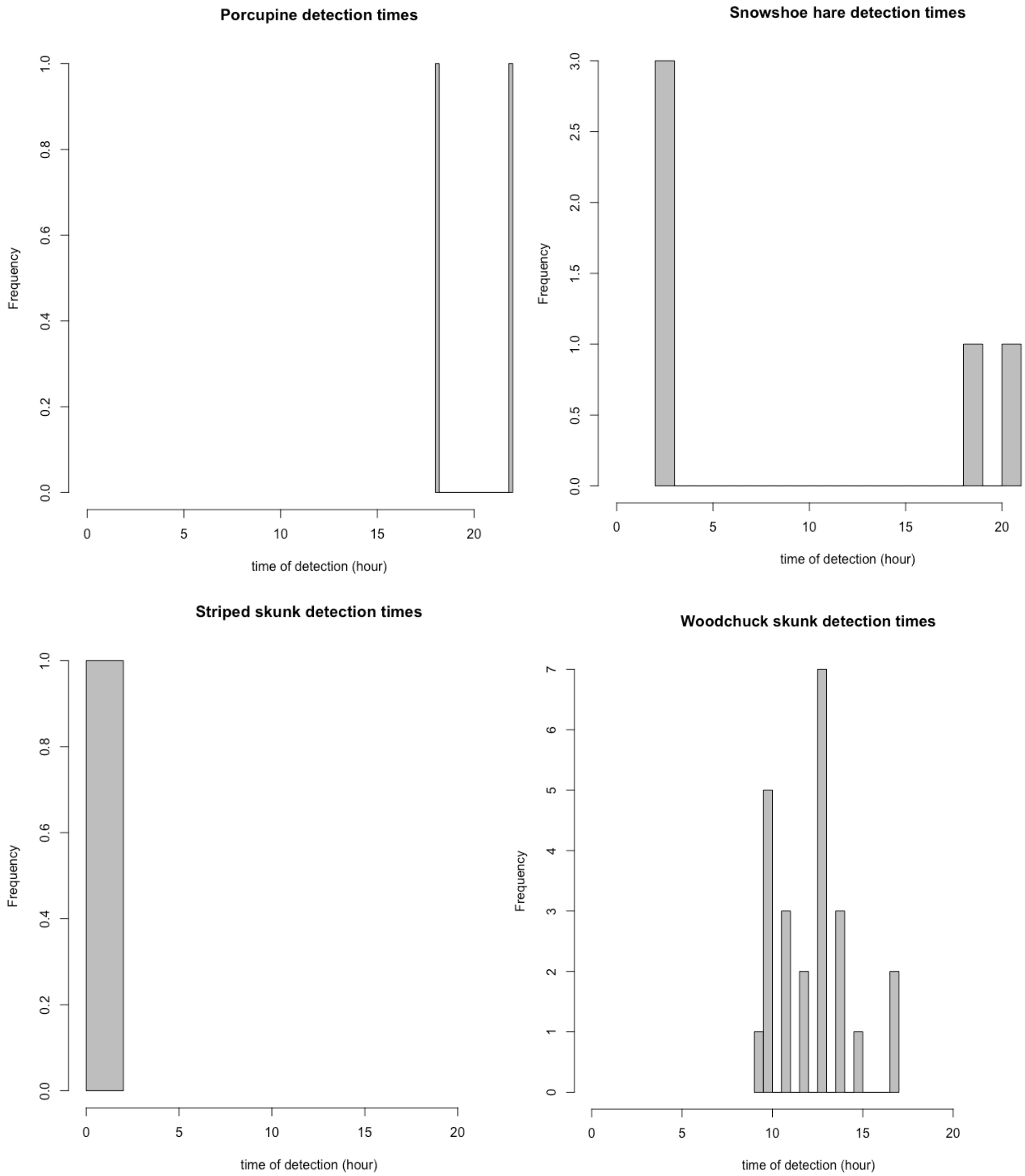


Figure B.2: Time of detection by species.

Tab. B.3: Track box results by species and culvert site:

	Culvert	M6	M7	2	3	4	8	11	14	15	17	21	22	28	
Species	Mouse spp.	21	23	25	24	20	24	22	26	28	22	23	21	25	304
	Eastern squirrel	10	12	10	9	8	7	10	15	13	18	6	6	11	135
	Raccoon	13	14	16	7	5	2	9	9	9	9	10	12	6	121
	Eastern chipmunk	4	3	4	2	2	7	3	4	2	4	7	8	4	54
	Vole	4	1	3	1	2	2	1	1	1	4	2	3	3	28
	Woodchuck	0	1	0	0	2	0	1	0	2	2	4	2	0	14
	Striped skunk	0	0	0	0	0	0	1	0	2	0	1	1	5	10
	Snowshow hare	1	1	0	0	3	2	0	0	0	0	2	0	0	9
	Dom. cat	0	0	0	0	0	0	1	2	5	0	0	0	0	8
	N. Am. porcupine	0	0	0	0	1	0	2	1	0	2	0	0	1	7
	Am. mink	1	2	1	2	0	0	0	0	0	1	0	0	0	7
	weasel spp.	0	0	0	1	1	0	2	0	0	1	1	0	0	6
	Muskrat	0	0	0	0	0	0	0	0	2	0	0	1	0	3
	N. Am. river otter	1	0	0	0	0	0	0	0	0	0	1	0	0	2
Sum	Total	55	57	59	46	44	44	52	58	64	63	57	54	55	

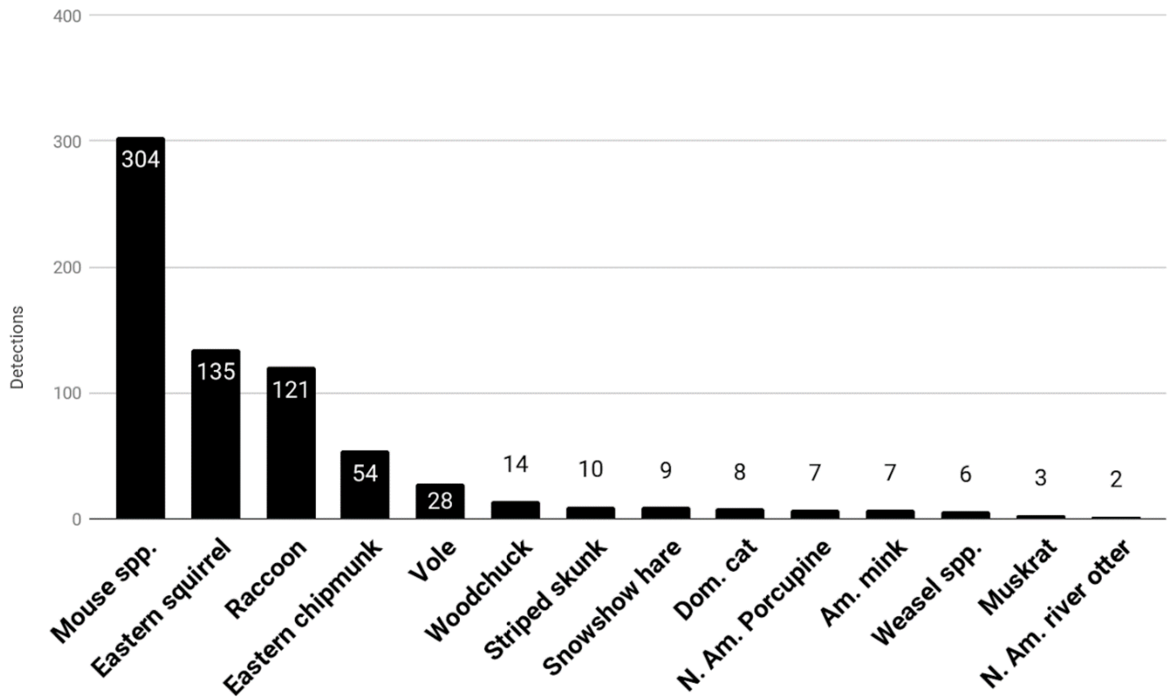
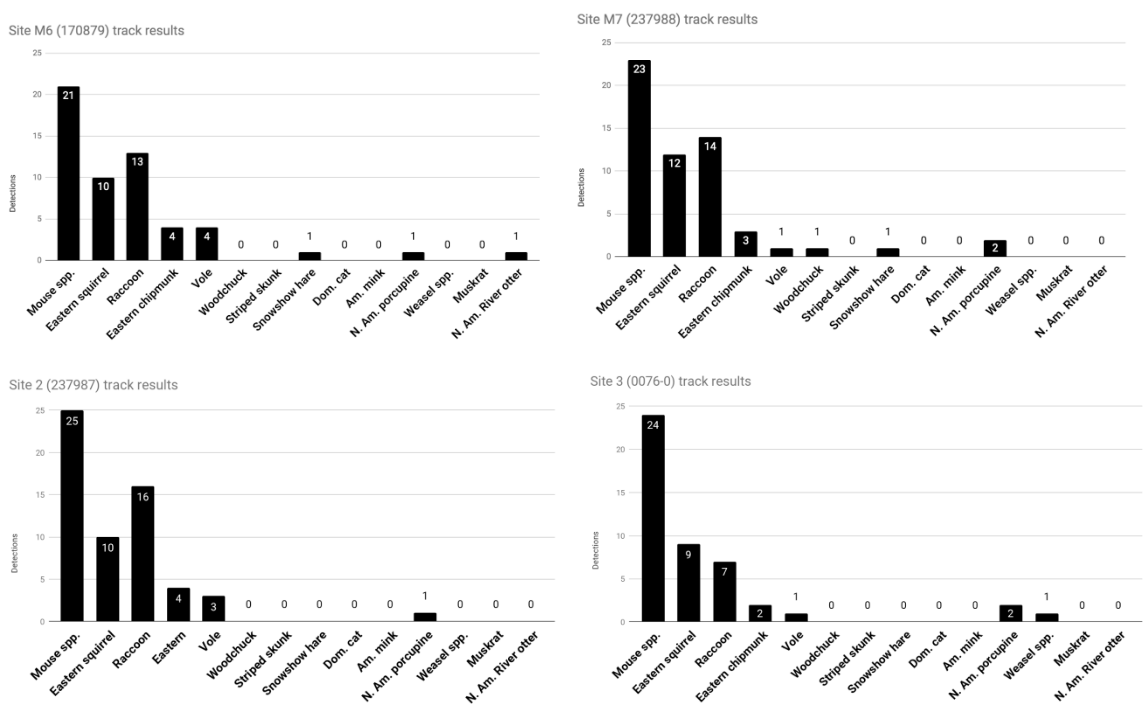
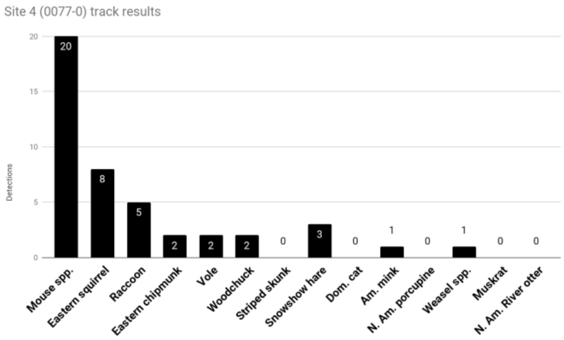
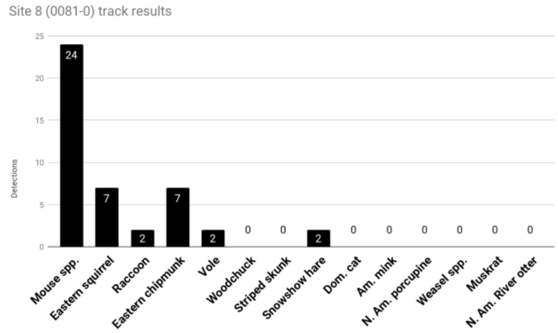
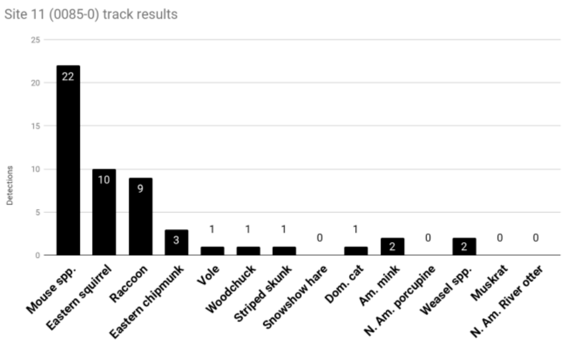


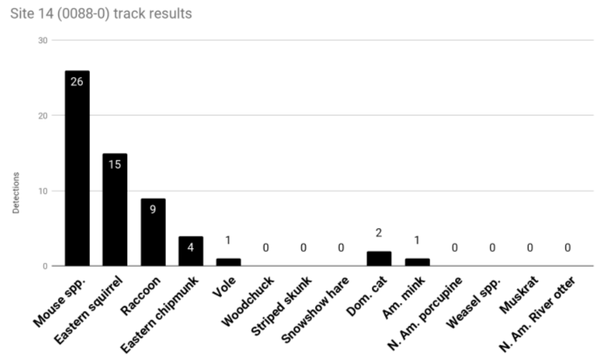
Fig. B.3: Track box results across all sites.

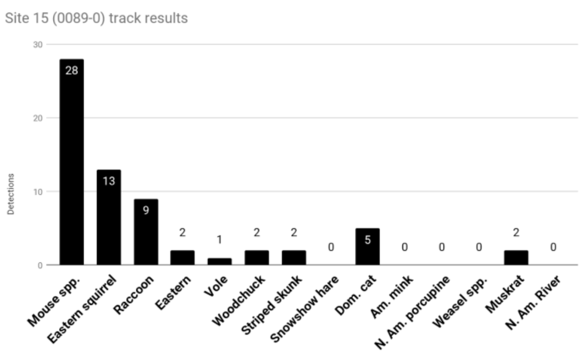


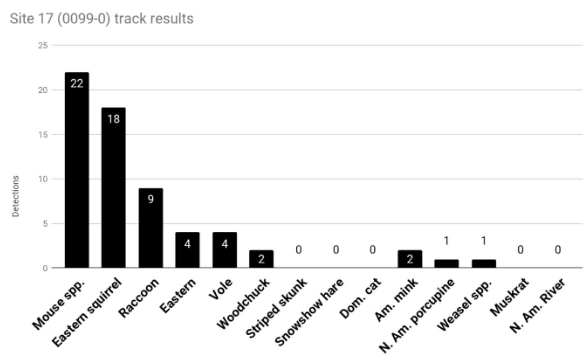

Site 4 (0077-0) track results
Detections
Mouse spp. 20
Eastern squirrel 8
Raccoon 5
Eastern chipmunk 2
Vole 2
Woodchuck 2
Striped skunk 0
Snowshow hare 3
Dom. cat 0
Am. mink 1
N. Am. porcupine 0
Weasel spp. 1
Muskrat 0
N. Am. River otter 0

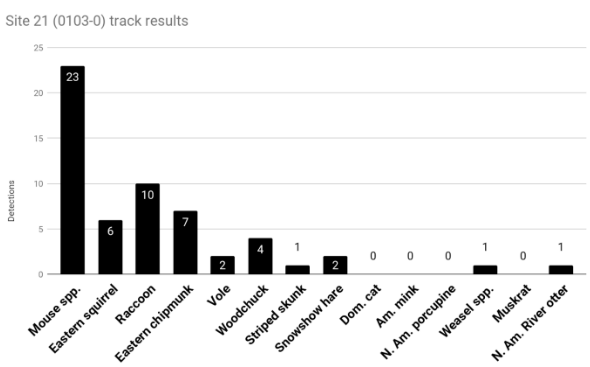

Site 8 (0081-0) track results
Detections
Mouse spp. 24
Eastern squirrel 7
Raccoon 2
Eastern chipmunk 7
Vole 2
Woodchuck 0
Striped skunk 0
Snowshow hare 2
Dom. cat 0
Am. mink 0
N. Am. porcupine 0
Weasel spp. 0
Muskrat 0
N. Am. River otter 0

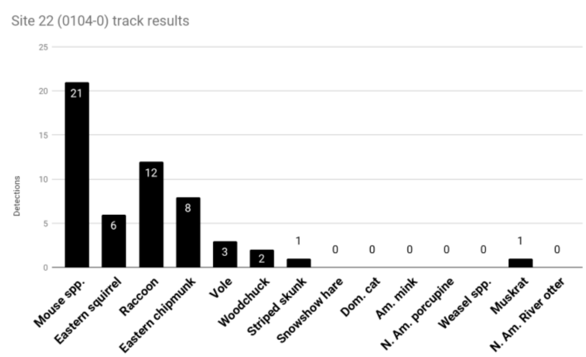

Site 11 (0085-0) track results
Detections
Mouse spp. 22
Eastern squirrel 10
Raccoon 9
Eastern chipmunk 3
Vole 1
Woodchuck 1
Striped skunk 1
Snowshow hare 0
Dom. cat 1
Am. mink 2
N. Am. porcupine 0
Weasel spp. 2
Muskrat 0
N. Am. River otter 0


Site 14 (0088-0) track results
Detections
Mouse spp. 26
Eastern squirrel 15
Raccoon 9
Eastern chipmunk 4
Vole 1
Woodchuck 0
Striped skunk 0
Snowshow hare 0
Dom. cat 2
Am. mink 1
N. Am. porcupine 0
Weasel spp. 0
Muskrat 0
N. Am. River otter 0


Site 15 (0089-0) track results
Detections
Mouse spp. 28
Eastern squirrel 13
Raccoon 9
Eastern 2
Vole 1
Woodchuck 2
Striped skunk 2
Snowshow hare 0
Dom. cat 5
Am. mink 0
N. Am. porcupine 0
Weasel spp. 0
Muskrat 2
N. Am. River 0


Site 17 (0099-0) track results
Detections
Mouse spp. 22
Eastern squirrel 18
Raccoon 9
Eastern 4
Vole 4
Woodchuck 2
Striped skunk 0
Snowshow hare 0
Dom. cat 0
Am. mink 2
N. Am. porcupine 1
Weasel spp. 1
Muskrat 0
N. Am. River 0


Site 21 (0103-0) track results
Detections
Mouse spp. 23
Eastern squirrel 6
Raccoon 10
Eastern chipmunk 7
Vole 2
Woodchuck 4
Striped skunk 1
Snowshow hare 2
Dom. cat 0
Am. mink 0
N. Am. porcupine 0
Weasel spp. 1
Muskrat 0
N. Am. River otter 1


Site 22 (0104-0) track results
Detections
Mouse spp. 21
Eastern squirrel 6
Raccoon 12
Eastern chipmunk 8
Vole 3
Woodchuck 2
Striped skunk 1
Snowshow hare 0
Dom. cat 0
Am. mink 0
N. Am. porcupine 0
Weasel spp. 0
Muskrat 1
N. Am. River otter 0

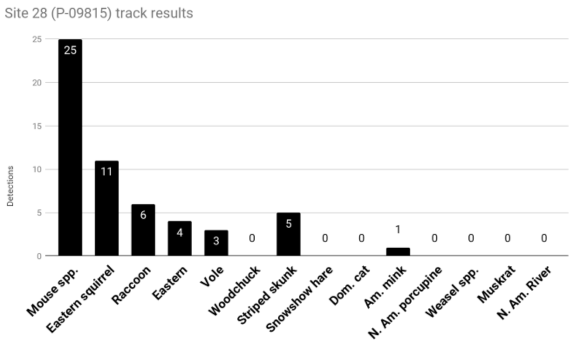


Figure B.4: Track box results by site.

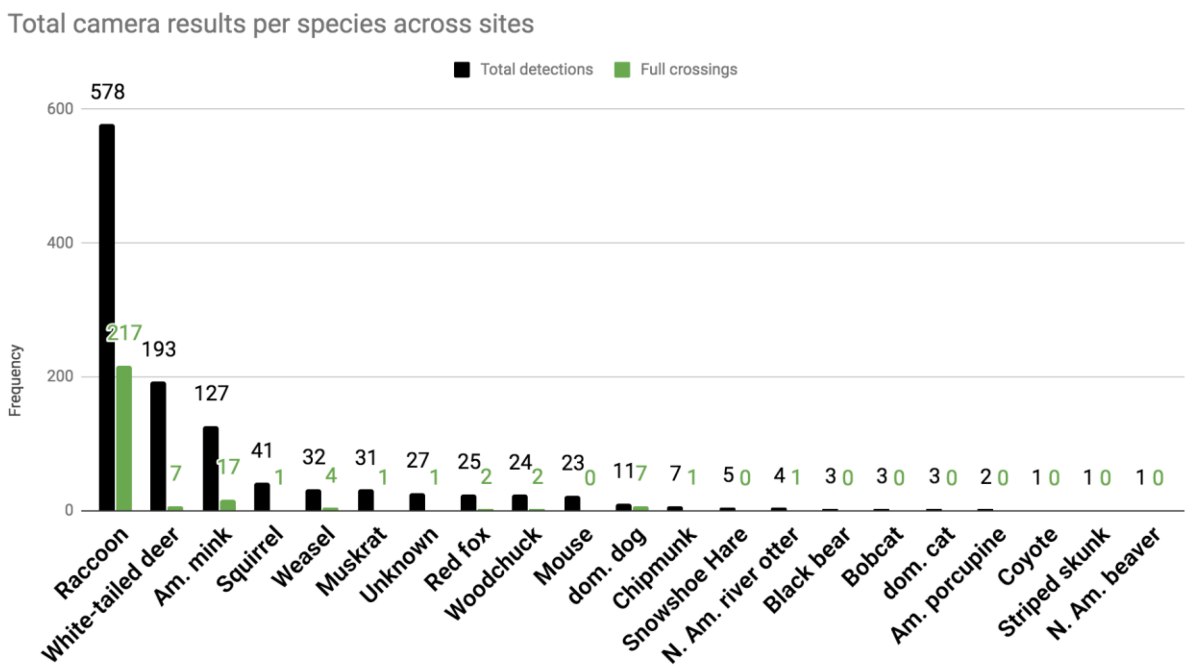


Fig. B.5: Camera results across all sites.

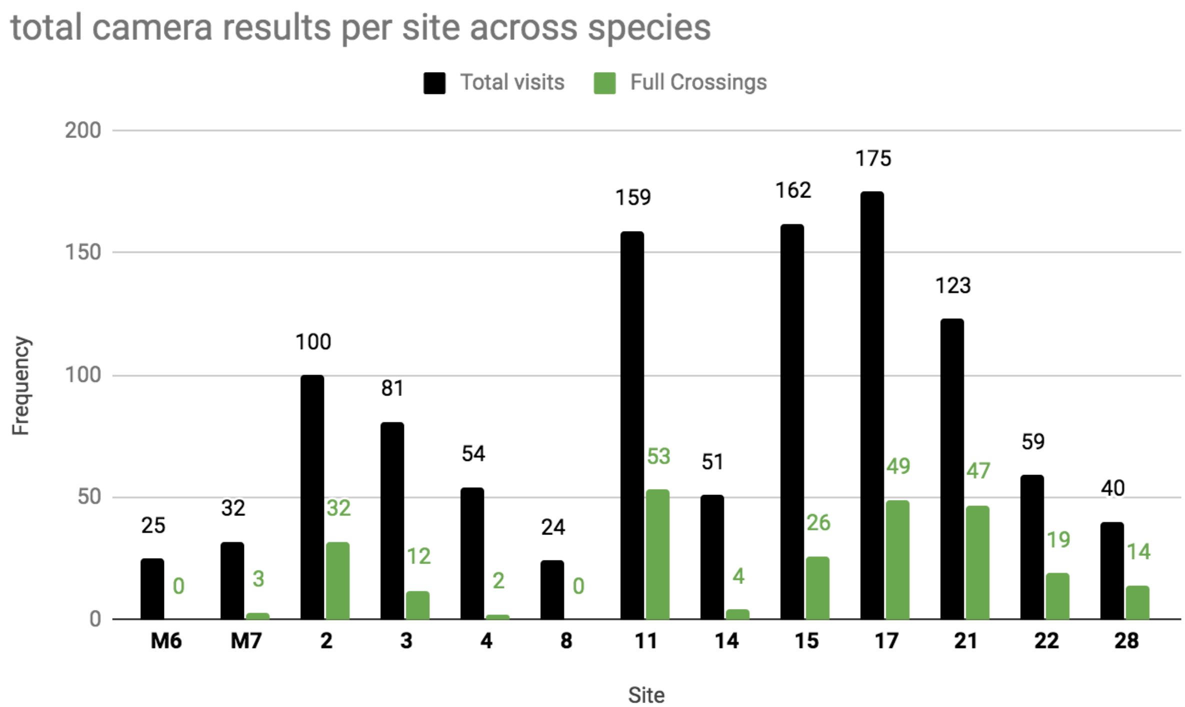
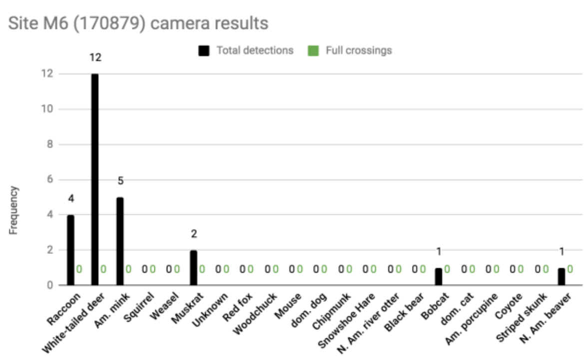
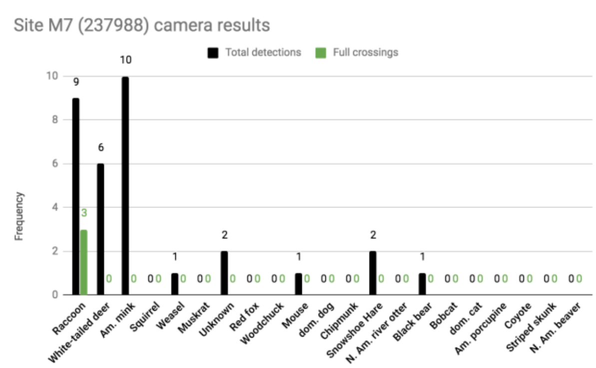
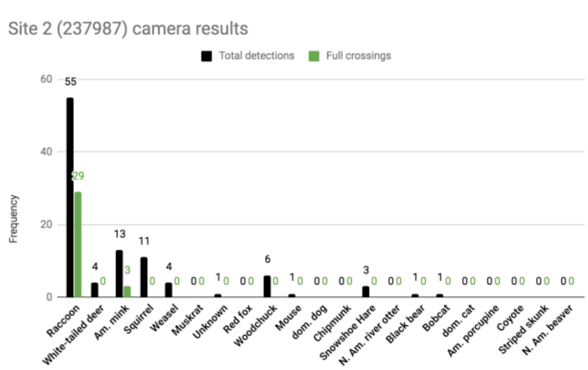
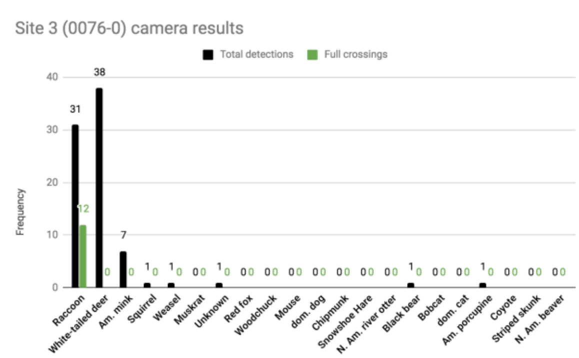


Fig. B.6: Summary of camera results by site.

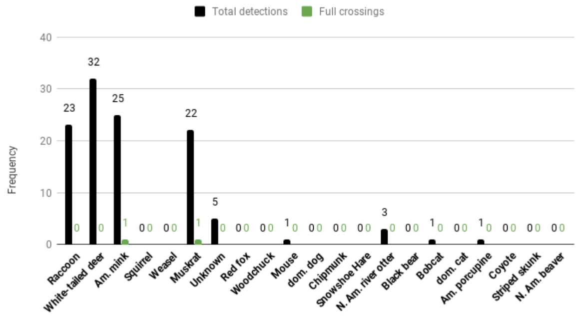




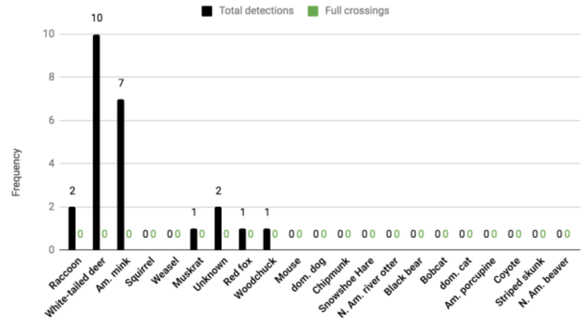




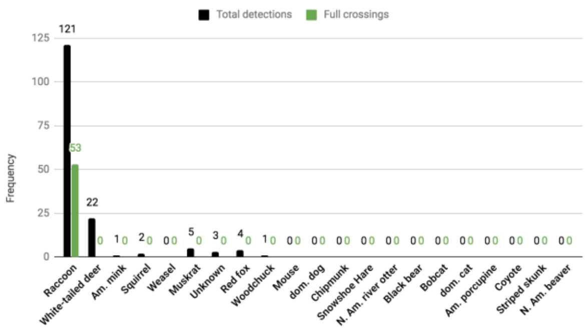
Site 4 (0077-0) camera results



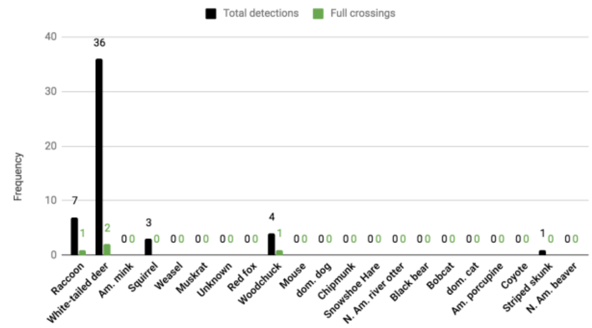
Site 8 (0081-0) camera results



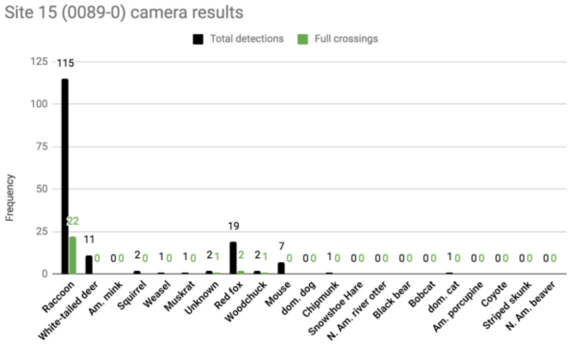
Site 11 (0085-0) camera results



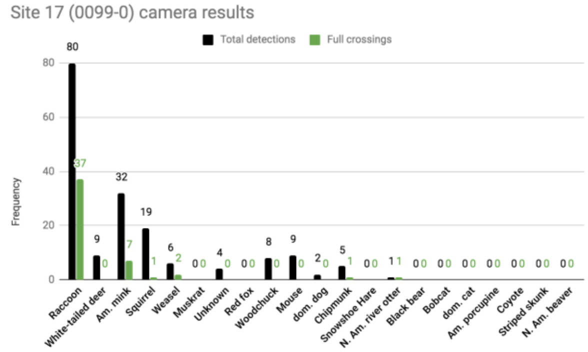
Site 14 (0088-0) camera results



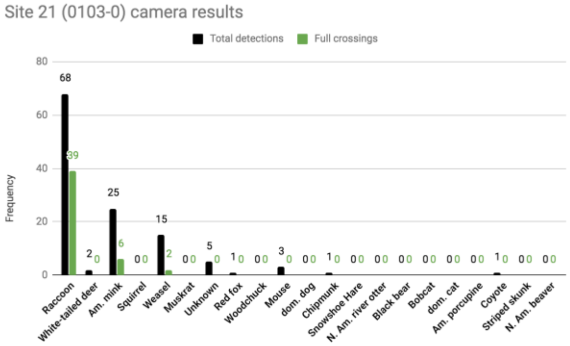
Site 15 (0089-0) camera results



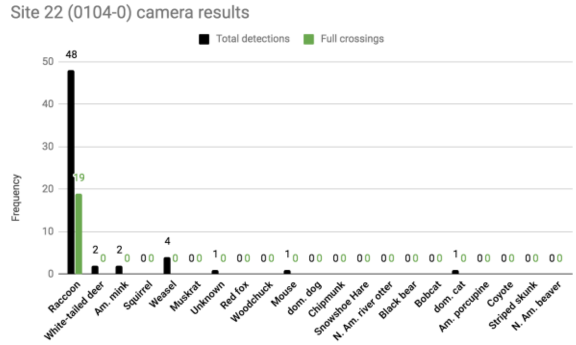
Site 17 (0099-0) camera results



Site 21 (0103-0) camera results



Site 22 (0104-0) camera results



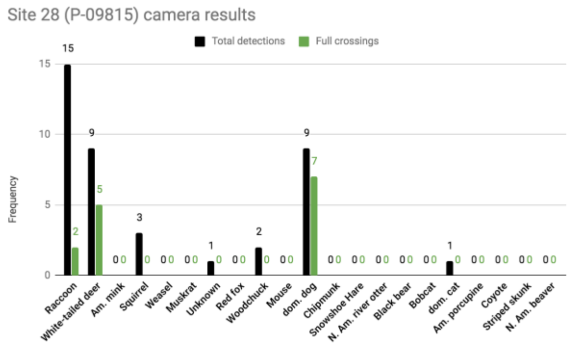


Fig. B.7: Camera results by site.

Tab. B.4: Comparison of ZINB GLMM final model with and without animal track variable

Model	Df	AIC	LLR	Marginal R^2
With trackavg	7	523.92	-254.96	0.1806
Without trackavg	6	532.65	-260.32	0.1009

Tab. B.5: Variance inflation factors for variables in each research question's global and final models.

Research Question	Model	Variable	Variance inflation factor
1	Final	Track average	1.0
		Temp (°C)	2.7
		Week	2.7
	Global	Track average	1.01
		Temp (°C)	3.47
		Week	3.01
		Material	NA
		Distance to forest (m)	1.87
		Corridor	1.07
		Length (cm)	1.83

		Water (cm)	1.34
		Rain (cm)	1.34
2	Final	Material	NA
		Distance to forest (m)	1.3
		Water (cm)	1.3
		qmoon	1.1
	Global	Material	NA
		Distance to forest (m)	1.62
		Water (cm)	1.31
		qmoon	1.91
		Corridor	1.04
		Length (cm)	1.50
		Temp (°C)	1.10
		Rain (cm)	1.02
3	Final	Corridor	1.1
		Distance to forest (m)	1.1
	Global	Corridor	2.54
		Distance to forest (m)	2.07
		Material	NA
		Length (cm)	1.60
		Water (cm)	1.86
		qmoon	1.36
		Temp (°C)	1.21
		Rain (cm)	1.06

PLOTS OF THE RESULTS

Research question 1:

Track average:

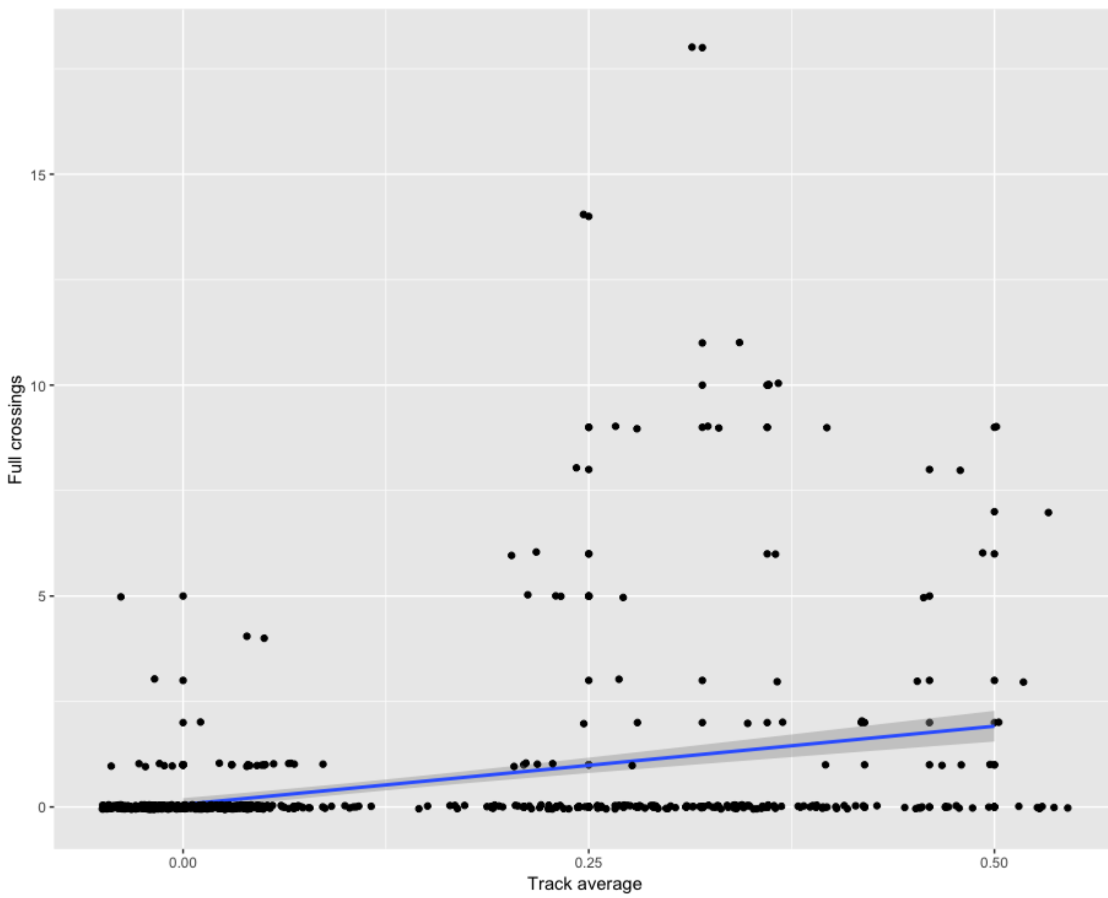


Fig B.8: Effect of track average per two-week period on the number of full passages (across all species).

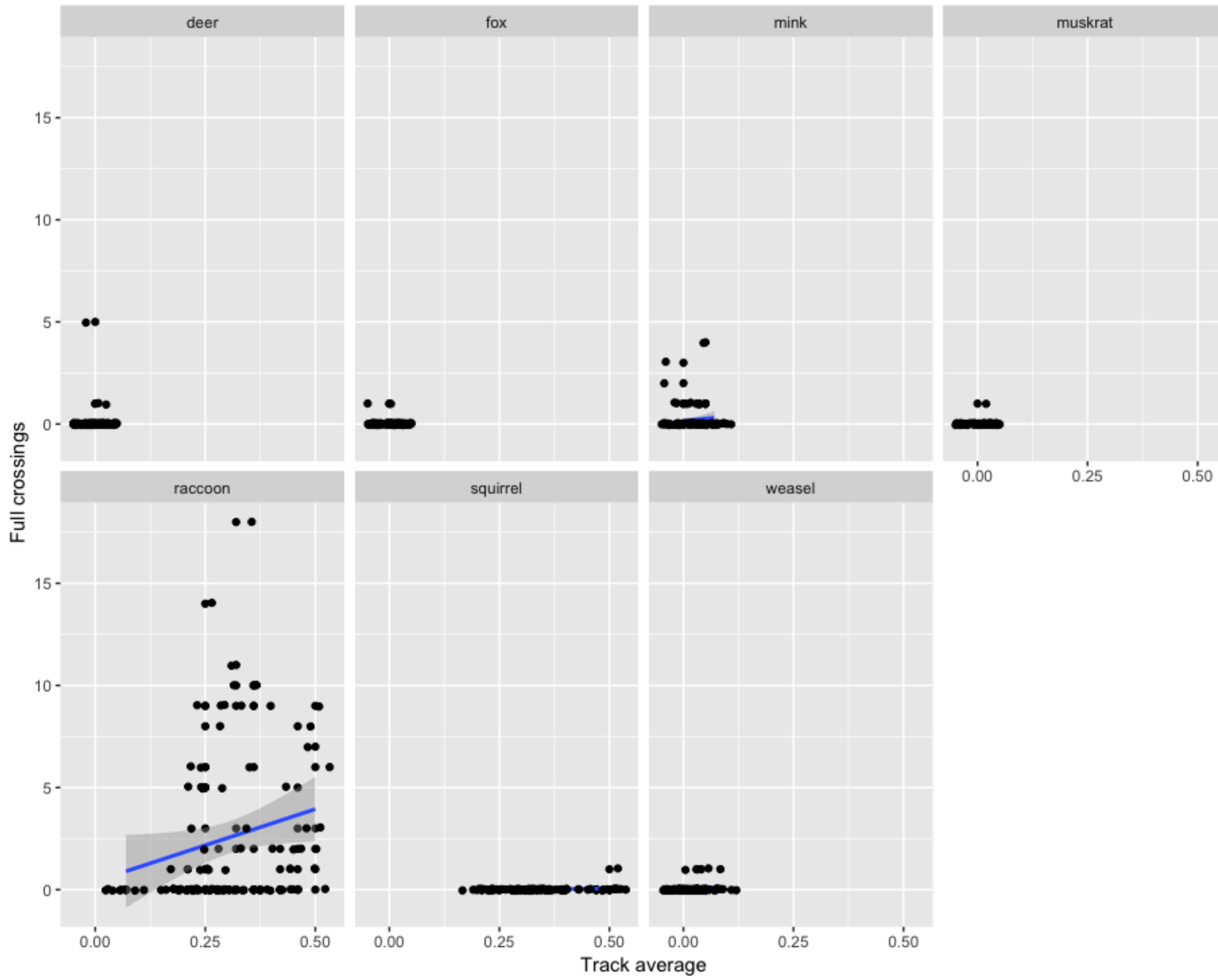


Fig. B.9: Effect of track average per two-week period on the number of full passages (by species).

Temperature:

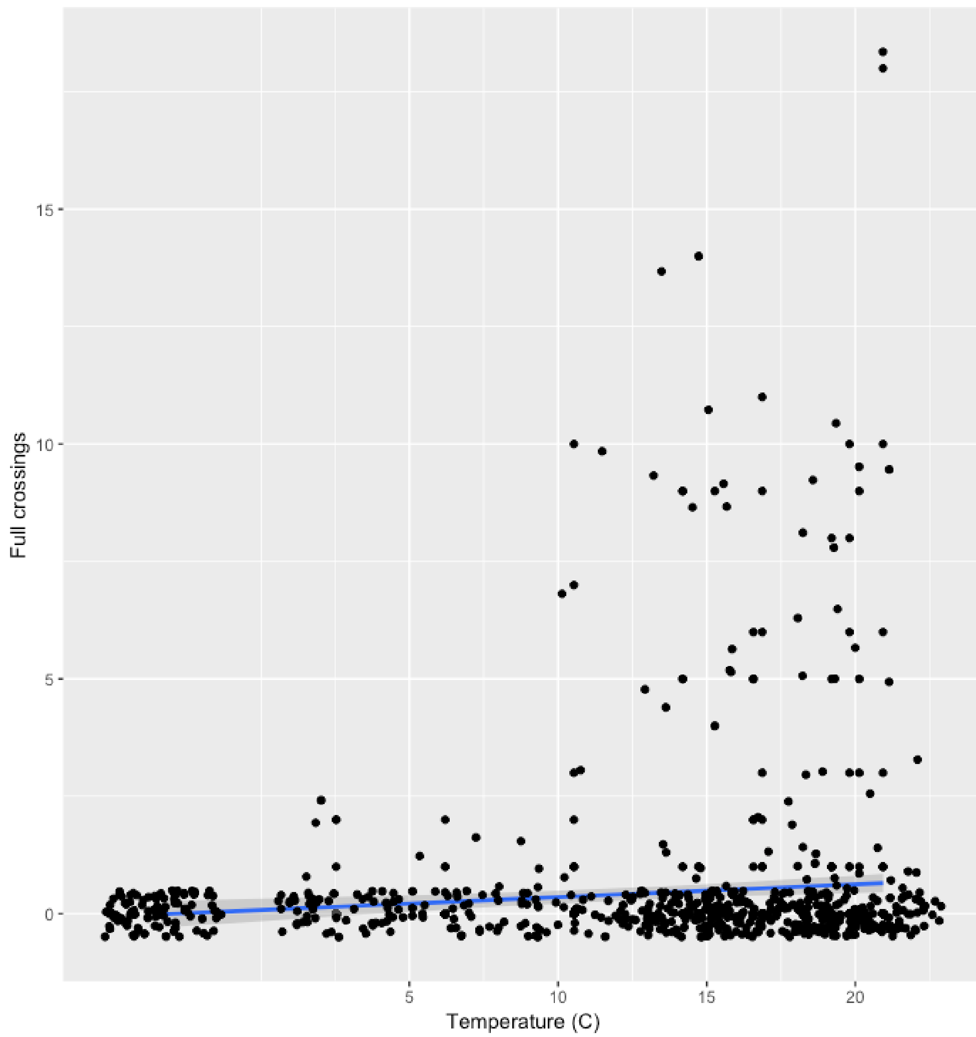


Fig. B.10: Effect of temperature on the number of full passages per two-week period (across all species).

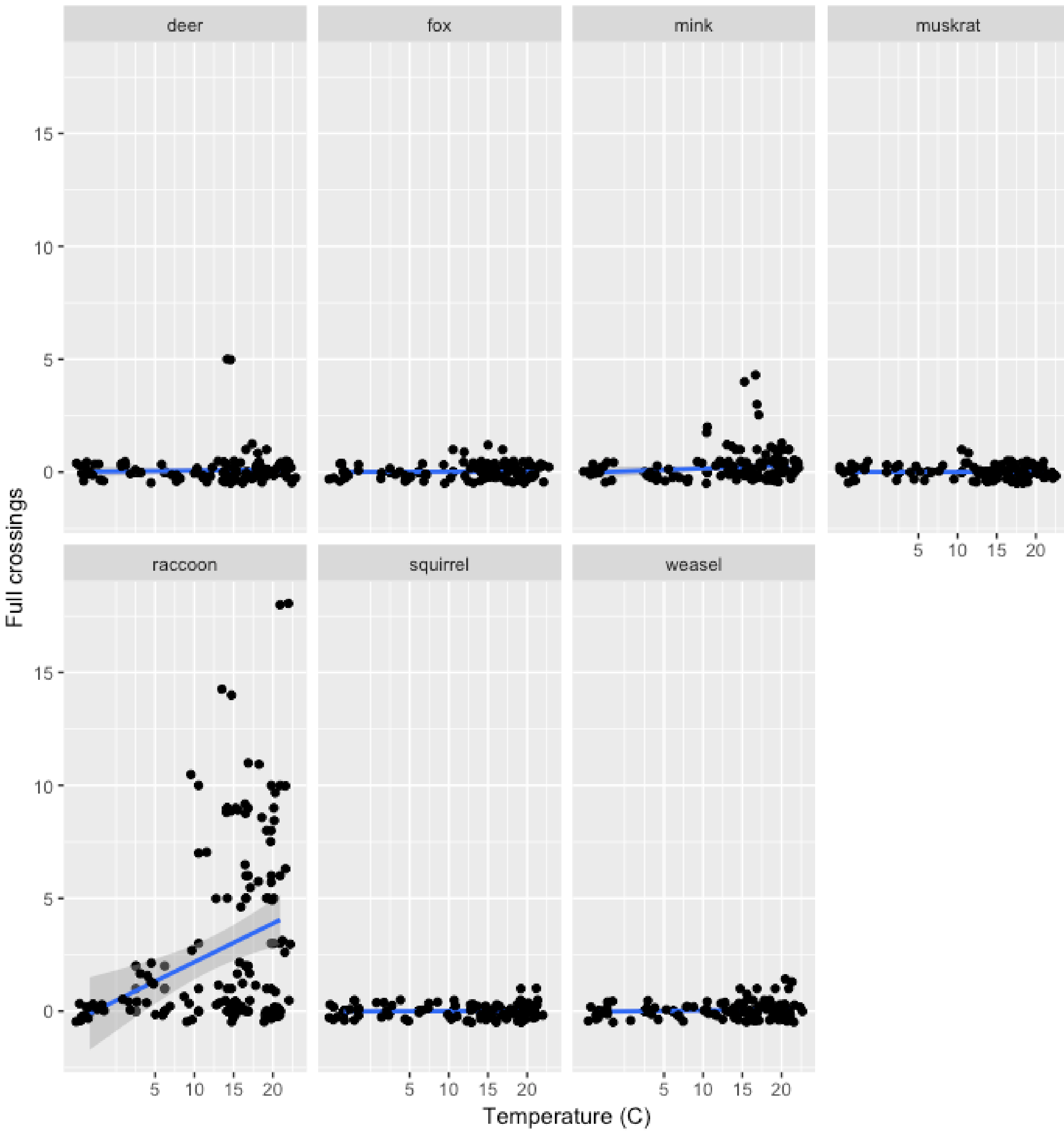


Fig. B.11: Effect of temperature on the number of full passages per two-week period (by species).

<u>Research question 2:</u>

Material:

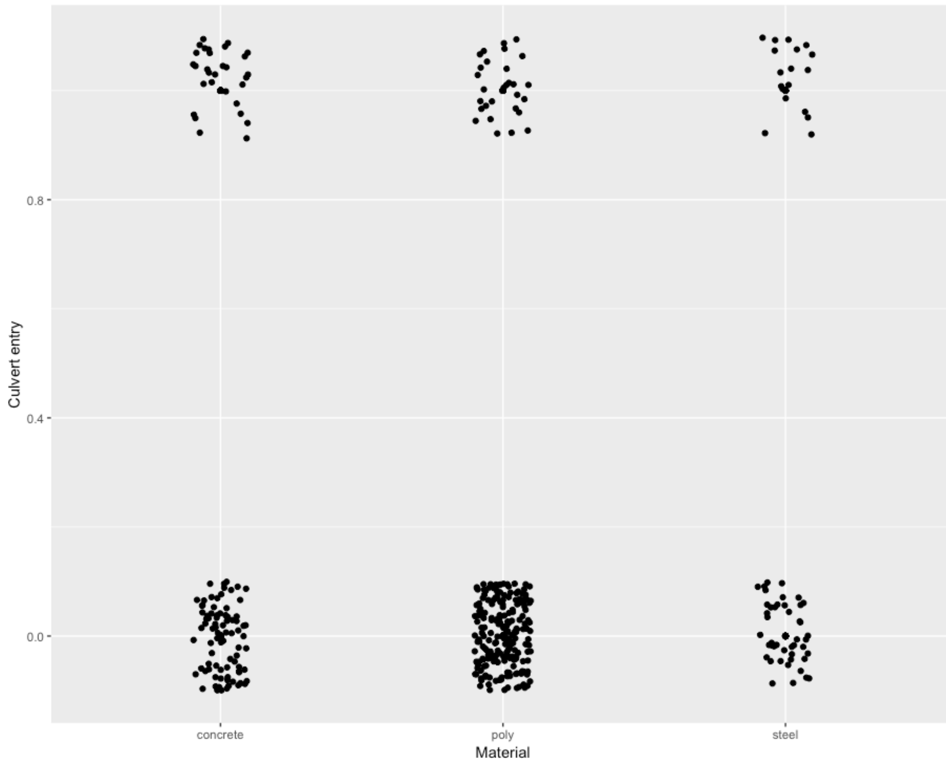


Fig. B.12: Effect of culvert material on the entry of mammals (across all species).

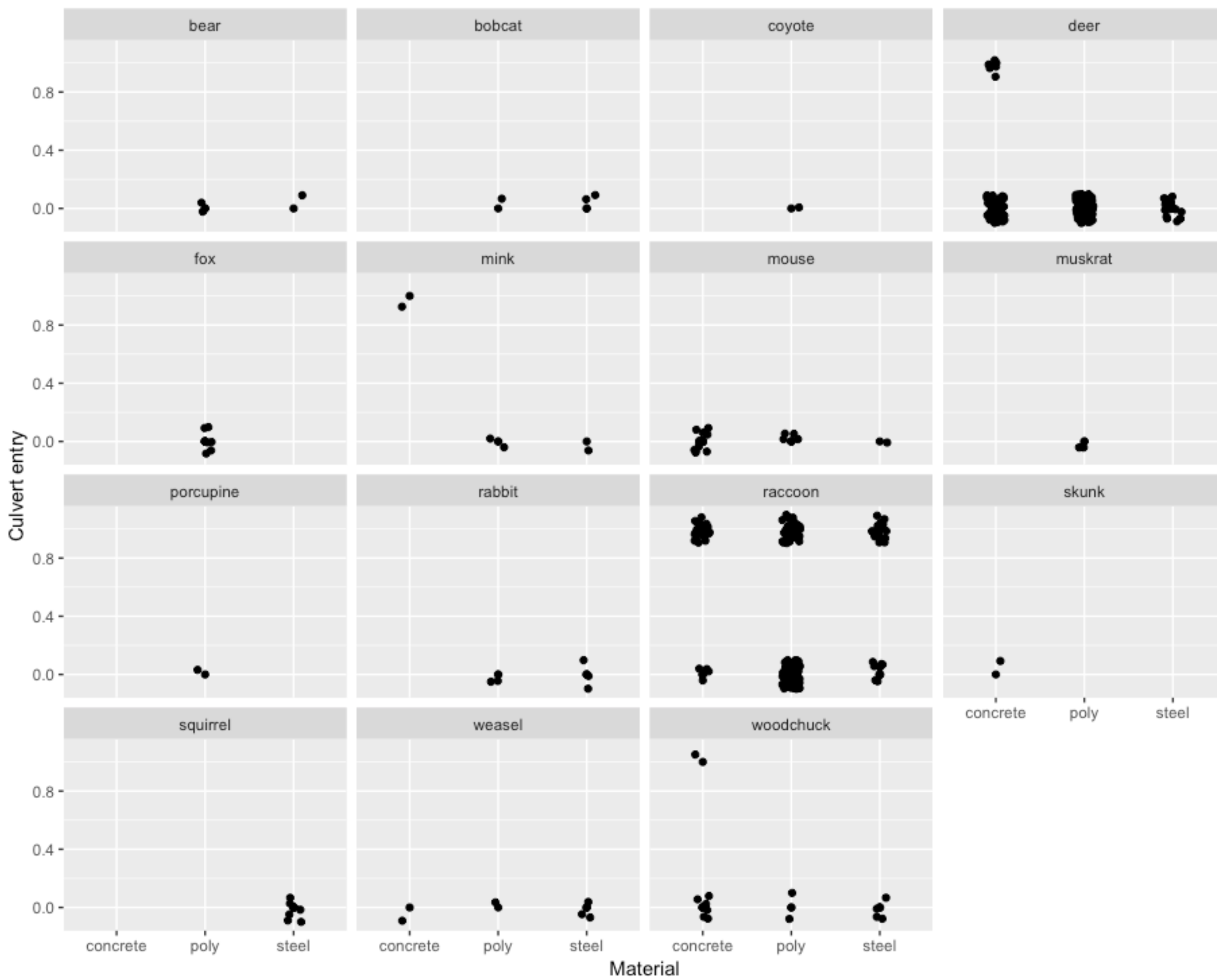


Fig. B.13: Effect of culvert material on the entry of mammals (by species).

Distance to forest edge:

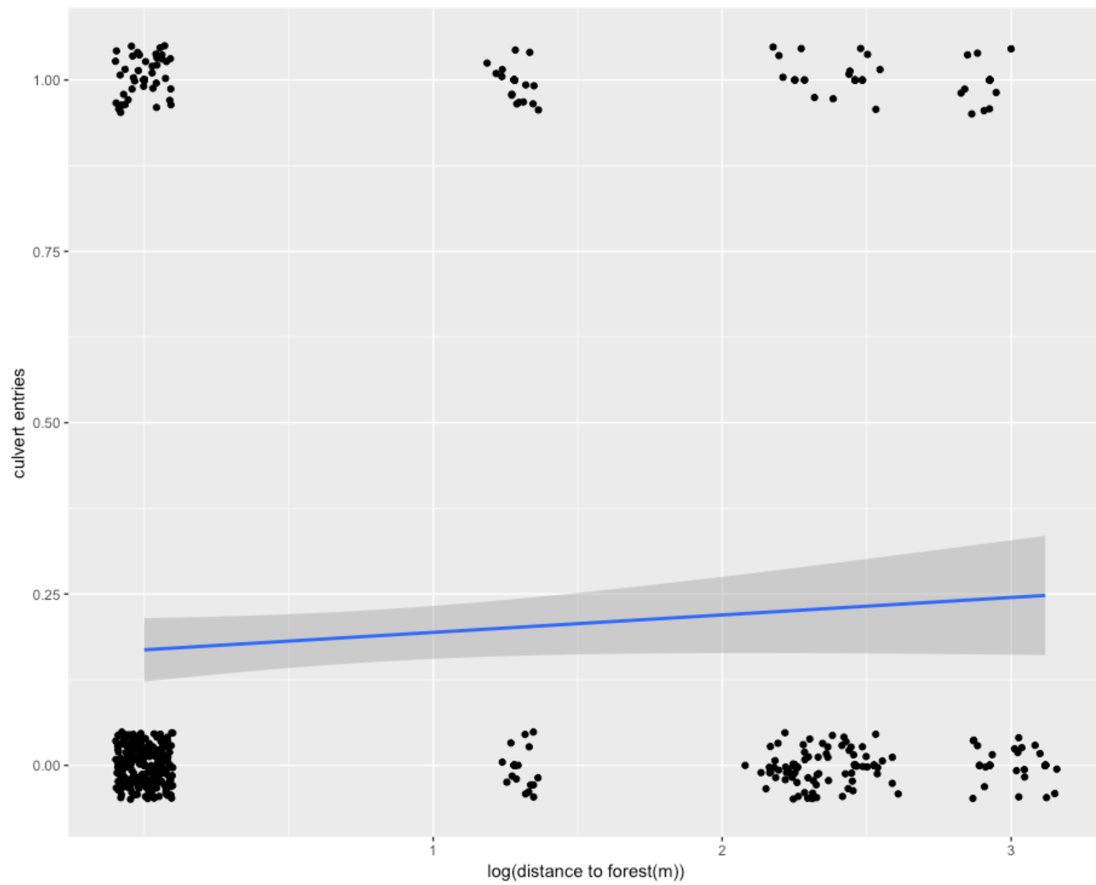


Fig. B.14: Effect of distance to the forest edge on entry into drainage culverts by mammals (across all species).

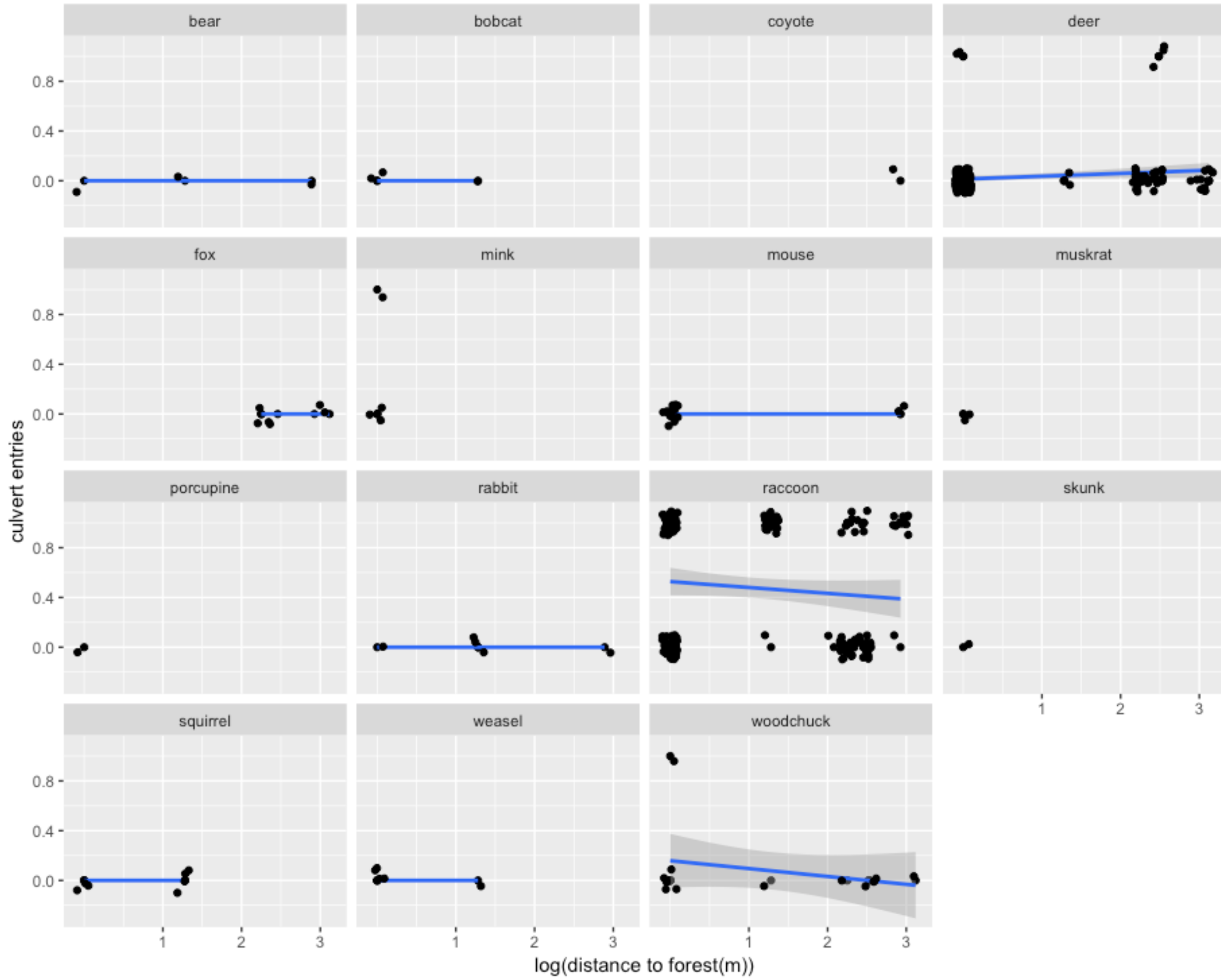


Fig. B.15: Effect of distance to the forest edge on entry into drainage culverts by mammals (by species).

Water:

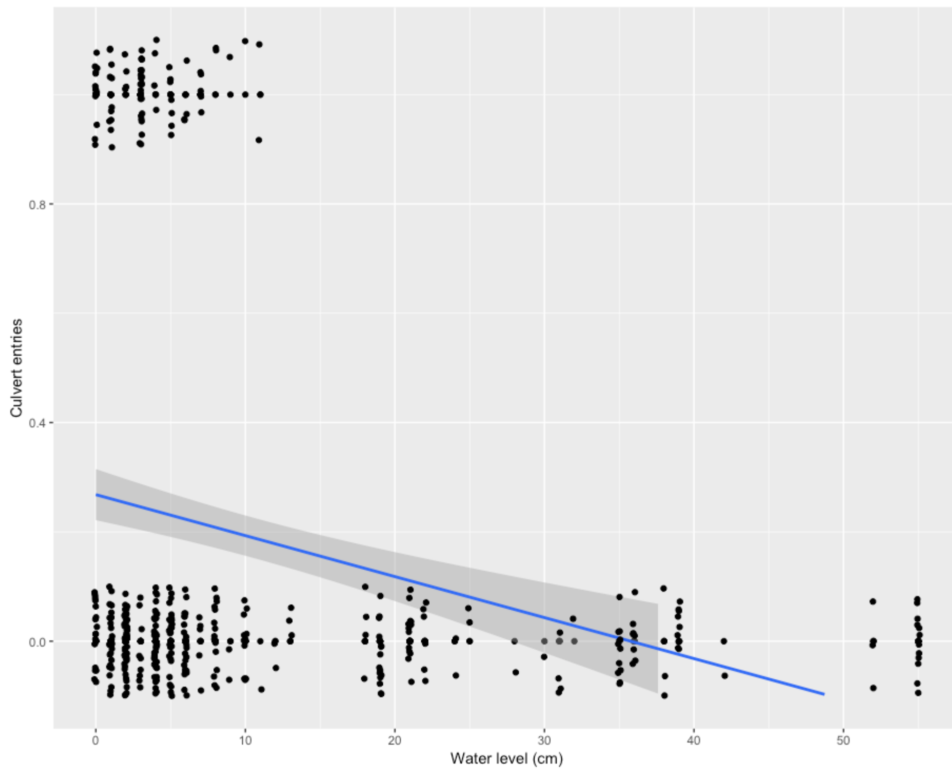


Fig. B.16: Effect of water level on the entry of drainage culverts by mammals (across all species).

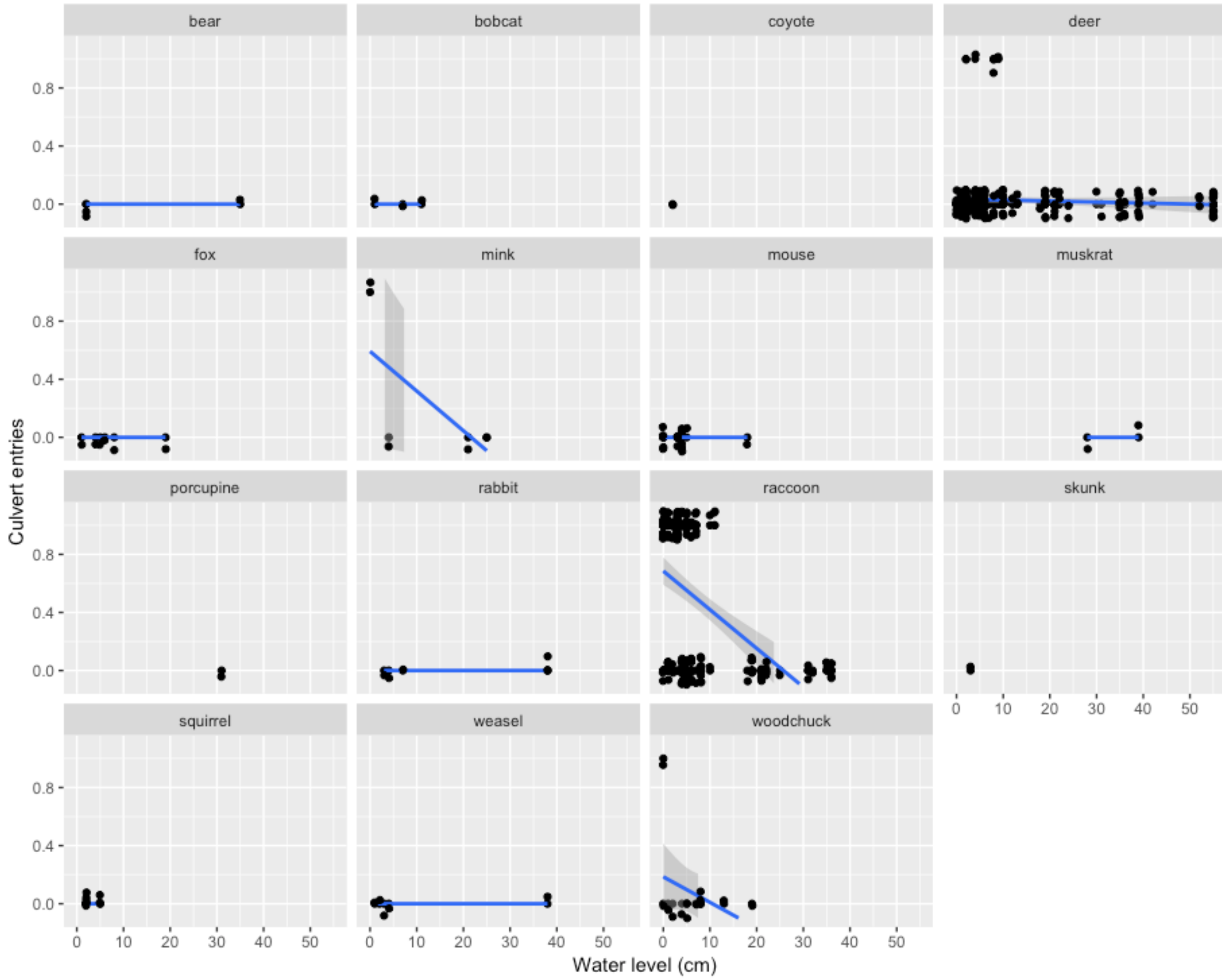


Fig. B.17: Effect of water level on the entry of drainage culverts by mammals (by species).

Moon luminosity:

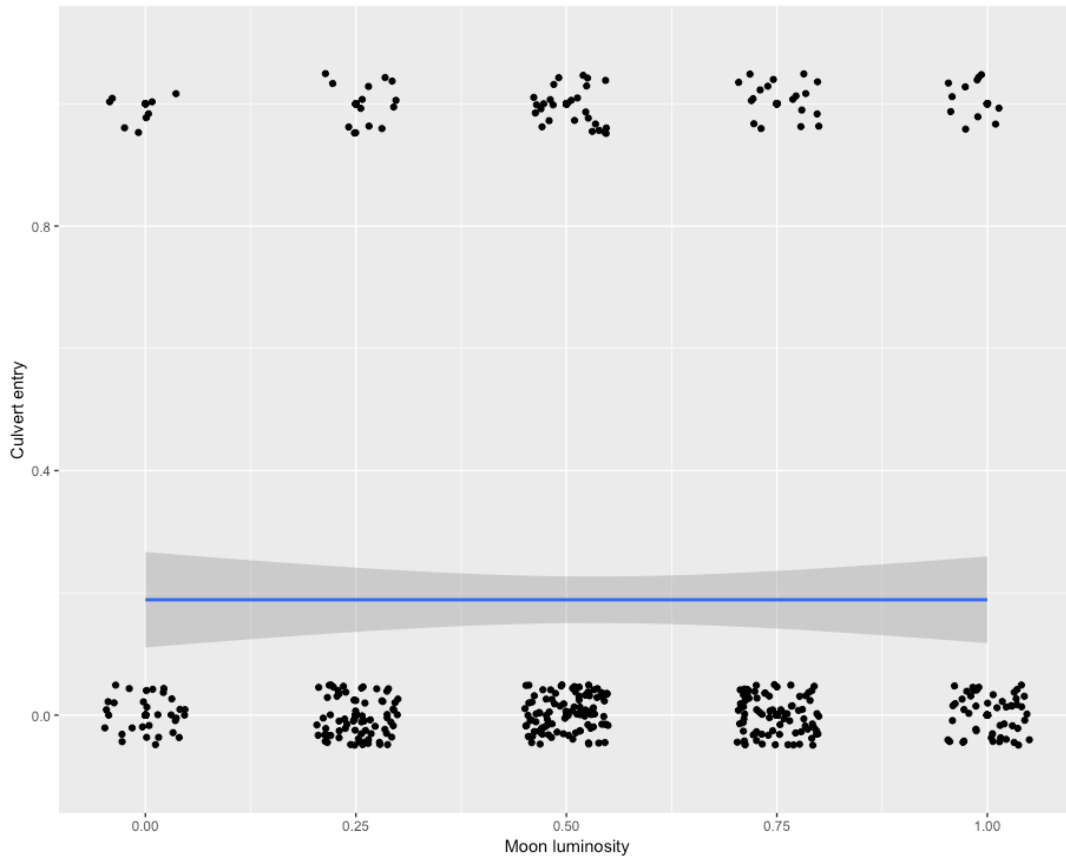


Fig.B.18: Effect of moon luminosity on the entry of drainage culvert by mammals (across all species).

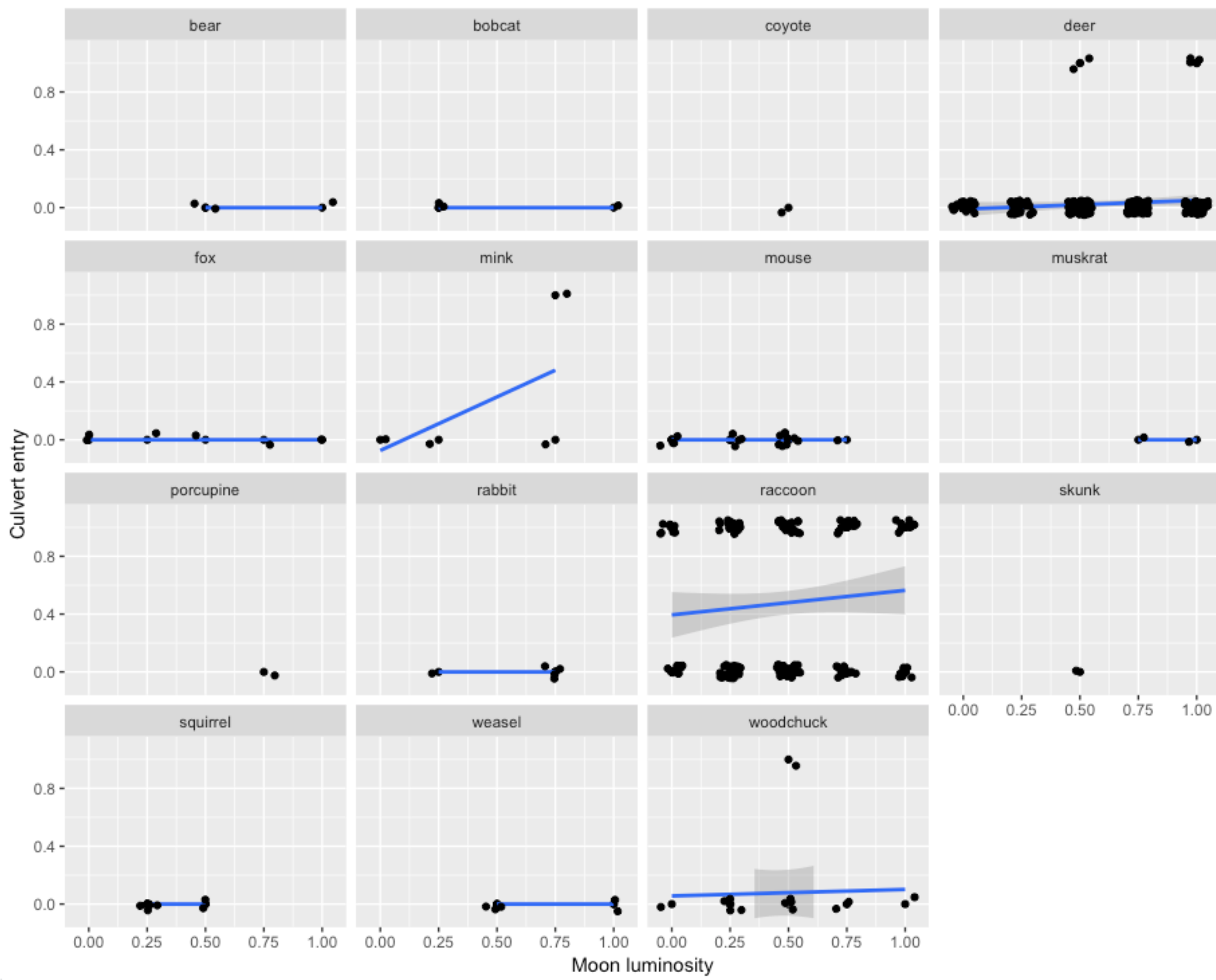


Fig. B.19: Effect of moon luminosity on the entry of drainage culvert by mammals (by species).

APPENDIX C

Performance indices

While it is highly useful to determine which drainage culvert factors across a study area influence the entry and full crossing of species, having site-specific metrics of passage suitability are particularly important for government and agency planners wishing to identify sites of high priority. This can be achieved through the implementation of performance indices, or ratios of observed full crossings by different species to expected full crossings (Clevenger & Waltho 2005). Performance indices are designed in such a way that the higher the value assigned to a particular site, the more effective the site is as a passage for that particular species (Clevenger et al. 2001).

Determining observed full passage values for each species was done solely using the camera data in this study, using two cameras at each drainage culvert entrance to confirm that an animal fully crossed from one side of the structure to the other without turning around. However, finding the expected full crossing values varies by study, and in some cases can become rather complex. For example, Clevenger and Waltho (2005) use a combination of two confounding variables to determine expected full crossing values for each species per site: (1) the variation in the density of crossing structures along the highway corridor, and (2) the equality of species' perceived access to each crossing structure. Here, we use a simplified metric to represent the number of expected full crossings: using only the camera data, the total number of detections per species per site, excluding detections with an unknown outcome. Values range from 0, representing the least suitable value for a passage for a given species, and 1, indicating that the drainage culvert allowed individuals from that species to fully cross 100% of the time. Values above 0.50 are highlighted (Table C.1).

Alternatively, we have created a second performance index using track paper data rather than camera data to determine the expected full-crossing values (Table C.2). This performance index takes into account the number of detections per species in the adjacent habitat of each site rather than at the entrance of the drainage culvert itself. The advantage of this method over the first, camera-based performance index is that it allows us to determine the suitability of a drainage culvert to facilitate an animal's full crossing based on its presence in the forest rather than when it is already in the cleared roadside. This gives an arguably more accurate picture of the presence and abundance of animals in this fragmented habitat. Its disadvantage is that fewer species were detected on the track papers than on the cameras at the drainage culverts, resulting in many cells being left blank due to lack of data. Additionally, because the probability that an individual will be detected at a track box differs between species due to the size of the track box, choice of scent lure, size of tracks, etc., performance index results using both track box data and trail camera data cannot be compared between species. Performance values for this index can exceed 1.00 because due to the use of two methods of data collection, situations arise where a species may fully cross a drainage culvert more times that it was detected by the track boxes.

Tab. C.1: Drainage culvert performance index using camera-confirmed full passages and detections.
* Average willingness to fully cross study area's drainage culverts

	Culvert													
	M6	M7	2	3	4	8	11	14	15	17	21	22	28	
Species	170879	237988	237987	0076-0	0077-0	0081-0	0085-0	0088-0	0089-0	0099-0	0103-0	0104-0	P-09815	*
Raccoon	0.00	0.60	0.74	0.75	0.00	0.00	0.71	0.00	0.79	0.82	0.95	0.76	0.67	**0.52**
Whitetail deer	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.56	**0.05**
Am. mink	0.00	0.00	0.75	0.00	0.20	0.00	0.00	0.00	0.00	0.88	1.00	0.00	0.00	**0.22**
Eastern squirrel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.00	0.00	**0.01**
Weasel spp.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.33	0.00	0.00	**0.10**
Muskrat	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.02**
Unknown	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	**0.08**
Red fox	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	**0.03**
Woodchuck	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	**0.15**
Mouse spp.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Dom. dog	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.78	**0.06**
Eastern chipmunk	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	**0.08**
Snowshoe Hare	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
N. Am. river otter	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	**0.08**
Black bear	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Bobcat	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Dom. cat	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
N. Am.porcupine	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Coyote	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Striped skunk	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
N. Am. beaver	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Average site performance	**0.00**	**0.03**	**0.07**	**0.04**	**0.02**	**0.00**	**0.03**	**0.05**	**0.15**	**0.23**	**0.11**	**0.04**	**0.10**	

Tab. C.2: Performance index using track box data to estimate expected full crossings.
* Average willingness to fully cross study area's drainage culverts

	Culvert													
	M6	M7	2	3	4	8	11	14	15	17	21	22	28	
Species	170879	237988	237987	0076-0	0077-0	0081-0	0085-0	0088-0	0089-0	0099-0	0103-0	0104-0	P-09815	*
Raccoon	0.00	0.21	1.81	1.71	0.00	0.00	5.89	0.00	2.44	4.11	3.90	1.58	0.20	**1.68**
Whitetail deer	-	-	-	-	-	-	-	-	-	-	-	-	-	**-**
Am. mink	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	3.50	1.50	0.00	0.00	**0.42**
Eastern squirrel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	**0.00**
Weasel spp.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.00	2.00	0.00	0.00	**0.31**
Muskrat	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Unknown	-	-	-	-	-	-	-	-	-	-	-	-	-	**-**
Red fox	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	**0.04**
Woodchuck	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Mouse spp.	-	-	-	-	-	-	-	-	-	-	-	-	-	**-**
Dom. dog	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.00	**0.02**
Eastern chipmunk	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Snowshoe Hare	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
N. Am. river otter	-	-	-	-	-	-	-	-	-	-	-	-	-	**-**
Black bear	-	-	-	-	-	-	-	-	-	-	-	-	-	**-**
Bobcat	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Dom. cat	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
N. Am.porcupine	-	-	-	-	-	-	-	-	-	-	-	-	-	**-**
Coyote	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Striped skunk	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Average site performance	**0.00**	**0.02**	**0.14**	**0.13**	**0.04**	**0.00**	**0.45**	**0.00**	**0.23**	**0.76**	**0.57**	**0.12**	**0.02**	

Regardless of which performance index we use, several things are clear: raccoons are comfortable using almost all of the drainage culverts in this study, and site 17 appears to be effective for a larger than average number of species. Raccoons are generalist animals, making this result not surprising. Site 17's effectiveness as a crossing structure, however, is very interesting. This site is a large concrete culvert (150 cm wide and 150 cm tall) with very little water flow (average depth throughout the sampling period was 1.77cm), making it a highly attractive means of crossing under the highway for several species. Moving forward, this drainage culvert should be left unaltered, and designated as a site of high priority for animal movement underneath Quebec's Autoroute 10.

Overall, the performance index using trail camera data for both full crossings and expected full crossings gave a more robust estimate of the performance of each drainage culvert to facilitate full crossings per species. Both the full crossing and expected full crossing metrics were from the same data source, making them more easily comparable than the second performance index, which compared full crossings confirmed by the trail cameras to presence counts of each species in the adjacent habitat using track papers. By using two separately sampled data sources for the second performance index (Table C.2), we encountered anomalies in the index including values over 1.00, and where species were not detected by the track papers, blank cells.