AN EMPIRICAL EVALUATION OF THE DETERMINANTS OF MOOSE-VEHICLE COLLISIONS ON THE ISLAND OF NEWFOUNDLAND, CANADA

by

© Amy L Tanner

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ABSTRACT

Moose-vehicle collisions (MVCs) are a problem throughout the circumpolar range of moose, but are especially prevalent on the island of Newfoundland, Canada. I designed a field study which determined that a common MVC mitigation strategy, roadside vegetation cutting, does not attract moose into roadside areas to browse. I also conducted a spatial analysis and identified small scale MVC hotspots scattered throughout the island, and medium and large scale MVC hotspots on primary roads and on the Avalon Peninsula. Finally, I used model selection to identify the best spatial predictors of the probability of occurrence of MVCs in Newfoundland. Specifically, primary roads, straight roads, decreased distance to large cities, and decreased distance to mining areas are associated with areas of high MVCs rates. This research provides managers with a basis for i) continuing roadside vegetation cutting and ii) implementing MVC mitigation strategies in strategic areas to reduce the number of MVCs.

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CHAPTER 1

General Introduction

There are more non-native and transient terrestrial mammal species than currently living native terrestrial mammal species in Newfoundland, Canada (Strong & Leroux, 2014). One of those introduced species is moose. Moose were first introduced to the island in 1878 when a bull and a cow from Nova Scotia were released near Gander Bay, and an additional four animals, two bulls and two cows, from New Brunswick were released near Howley in 1904 (Pimlott, 1953) (Fig. 1-1). Other than humans, the only potential predator for adult moose in Newfoundland, grey wolves (*Canis lupus*), were extirpated from the island approximately 100 years ago (Bergerud, Nolan, Curnew, & Mercer, 1983). Since their introduction, the moose population in Newfoundland peaked at 148,900, and through active management has been reduced to approximately 116,400 individuals (P. Saunders, personal communication, June 15, 2015). Newfoundland moose densities are among the highest across the global distribution of this species, ranging from 0.41 to more than 7.0 moose/km^2 (Joyce & Mahoney, 2001).

Moose are most often resident individuals but some populations do exhibit migratory behaviour (Hundertmark, 1998). For example, some moose in Alaska may migrate to areas with lower snow depths and snow persistence in winter (MacCracken, Van Ballenberghe, & Peek, 1997). Home ranges sizes of moose can be variable. For example, MacCracken et al. (1997) found the mean summer home range size of moose in Alaska to be 55km^2, while in northern Maine, Leptich and Gilbert (1989) found the mean summer home range size to be 25km^2. Moose vary in physical size, but as a whole, moose are the largest member of the Cervidae family (Franzmann, 1978), standing between 1.95-2.25m (6'5"-7'5") in height (Whitaker (Jr.), 1996). Bull moose weigh between 400-635kg (900-1,400 pounds) and cow moose weigh between 315-500kg (700-1,100 pounds) (Whitaker (Jr.), 1996). The antlers on bull moose are between 1.2 to 1.5m in size (4'-5') (Whitaker (Jr.), 1996), and are usually shed in the winter after the rut (Bubenik, 1998). Cows can begin breeding as yearlings, around one and a half years of age, and continue to reproduce until 18 years of age, with their highest reproductive potential between four to 12 years of age (Bubenik, 1998). Cows will usually have one calf per year, but are also known to have twins, and even triplets (Bubenik, 1998).

Due to their high abundance, and large body size, moose are important for both the economy and culture of Newfoundland. Moose were originally introduced to the island for subsistence local hunting and to attract sport hunters to the area (Howley, 1913; McLaren, Roberts, Djan-Chékar, & Lewis, 2004). Every year from September through January there is a large recreational hunt where approximately 31,000 moose hunting licenses are issued across 54 moose management areas (Department of Environment and Conservation, 2015). Recent hunting success rates range from 38% to 95% depending on the region, resulting in the harvesting of approximately 20,000 individual moose per year (Department of Environment and Conservation, 2015). Moose hunting provides licensed residents with moose meat for consumption and it greatly benefits the provincial outfitting industry, with approximately 4,000 non-resident licenses issued each year (Department of Environment and Conservation, 2015).

1.1 Overview of Ungulate-Vehicle Collisions

Despite the socio-economic benefits of moose to Newfoundlanders, there are negative interactions between humans and moose in Newfoundland, and throughout the entire range of moose. With increasing road density, there is an increase in the probability of ungulate-vehicle collisions as these roads infiltrate natural areas. Collisions with large ungulates, specifically moose, often lead to serious injuries to humans or even death (Oosenbrug, Mercer, & Ferguson, 1991). In Newfoundland alone, from 2000 to 2010 there were approximately 4,400 moose-vehicle collisions (MVCs), resulting in 900 human injuries and 18 human fatalities (Policy, Planning, and Evaluation Division, 2014). In 2011, a class-action lawsuit was filed against the Government of Newfoundland and Labrador for allegedly failing to adequately control the moose population. In addition to the threat ungulates pose to human safety, there are significant implications of ungulate-vehicle collisions on revenue. Huijser, Duffield, Clevenger, Ament, and McGowen (2009) estimated the average cost associated with a deer, elk, or moose-vehicle collision based on a review of the literature available. The cost of a single collision was estimated at $6,671, $17,483, and $30,760 (USD$ 2007) for deer, elk, and moose respectively (Huijser et al., 2009). With thousands of ungulate-vehicle collisions occurring across the geographic range of ungulates (AMEC Earth & Environmental, 2003; Huijser et al., 2008) this constitutes a substantial monetary cost.

The issue of MVCs is widespread, having a significant effect on both the culture and economy of the affected areas. This has resulted in the implementation of mitigation strategies to reduce the number of collisions. Studies throughout Canada (e.g., Dussault, Poulin, Courtois, & Ouellet, 2006; Huijser et al., 2009; Hurley, Rapaport, & Johnson, 2007; Joyce & Mahoney, 2001; Rea, Johnson, & Emmons, 2014), the United States (e.g., Danks & Porter, 2010; Litvaitis & Tash, 2008; Olson et al., 2015; Sawyer, Lebeau, & Hart, 2012; Snow, Williams, & Porter, 2014) and Europe (e.g., Elmeros, Winbladh, Anderson, Madsen, & Christensen, 2011; Hothorn, Brandl, & Müller, 2012; Malo, Suarez, & Diez, 2004; Putzu et al., 2014; Seiler, 2005) have been conducted with the goal of reducing the number of ungulate-vehicle collisions.

1.2 Common Wildlife-Vehicle Collision Mitigation Strategies

Many different mitigation strategies have been developed and implemented to reduce the number of wildlife-vehicle collisions (WVCs) (see reviews of some strategies in Huijser et al., 2009; Huijser et al., 2008). Some common mitigation strategies include, but are not limited to roadside fencing, wildlife warning signs, modifying roadside vegetation, warning reflectors, population culling, and animal detection systems. Some strategies are physical barriers to animal movement, such as fencing (Clevenger, Chruszcz, & Gunson, 2001), while other strategies deter animals from crossing the road, such as warning reflectors (Schafer & Penland, 1985). Other strategies seek to warn drivers about animal presence, such as temporary wildlife warning signs (Sullivan, Williams, Messmer, Hellinga, & Kyrychenko, 2004) or animal detection systems (Huijser & McGowen, 2003). Each mitigation strategy has pros and cons, with the level of effectiveness of the strategy depending on a number of factors. For example, wildlife fencing has been found to be very effective (Clevenger et al., 2001), but without crossing structures, it can obstruct animal movement and could ultimately reduce gene flow within target and non-target animal populations (Olsson & Widen, 2008). Huijser et al. (2009) provides an overview of studies focusing on mitigation measures for ungulate-vehicle collisions and their level of effectiveness. A common mitigation strategy is roadside vegetation cutting, also known as roadside brush cutting, where the vegetation is cut back along the edges of roads. Roadside vegetation cutting is performed to increase road safety by increasing driver visibility (AMEC Earth & Environmental, 2004; Child, 1998). In my thesis, I provide the first empirical evaluation of the effectiveness of roadside vegetation cutting with regards to moose browsing, rather than increased driver visibility.

1.3 Hotspots for MVCs

WVCs are often spatially clustered and these clusters are referred to as collision "hotspots" (Litvaitis & Tash, 2008). Spatial clustering of collisions occurs for many different species including, but not limited to, porcupines, raccoons (Barthelmess, 2014), turtles (Beaudry, Demaynadier, & Hunter, 2008), moose (Danks & Porter, 2010), and kangaroos (Ramp, Caldwell, Edwards, Warton, & Croft, 2005). WVCs may occur in spatially clustered patterns for many reasons, such as accumulations of salt near roadways, migration routes, and proximity to wetlands (Litvaitis & Tash, 2008; Lloyd & Trask, 2005). WVC hotspots should be the first to receive mitigation strategies because these areas pose an increased risk to human and animal safety. Identifying WVC hotspots is crucial because it may allow management officials to implement the most effective and cost-efficient strategies to reduce the number of WVCs in a time sensitive manner.

1.4 Spatial Correlates of Ungulate-Vehicle Collisions

In an attempt to effectively reduce the frequency of WVCs, many studies have been conducted to determine the most common environmental and spatial variables associated with collision locations (review in Gunson, Mountrakis, & Quackenbush, 2011). The ultimate goal of these studies is to identify correlates of WVCs to inform and prioritize management actions. Key correlates of WVCs may differ among sites as local environmental conditions are context dependent. Some factors such as traffic volume and speed limit, however, are generally found to be positively correlated with the probability of WVC occurrence (e.g., Danks & Porter, 2010; Gunther, Biel, & Robison, 1998; Joyce & Mahoney, 2001; Seiler, 2005). Common factors included in the spatial analysis of ungulate-vehicle collisions are topography (e.g., terrain slope – Dussault et al., 2006; Hurley et al., 2007), land cover (e.g., proportion or percent of land cover types – Danks & Porter, 2010; Hothorn et al., 2012; Malo et al., 2004; Seiler, 2005), and study species density (e.g., moose density – Dussault et al., 2006; Joyce & Mahoney, 2001), along with many others.

In my thesis, I conduct an analysis of the key determinants of MVCs on the island of Newfoundland, Canada and I provide the first empirical assessment of a very common WVC mitigation strategy – roadside vegetation cutting, which is used as a mitigation strategy throughout the geographic range of many ungulates. In the following chapters I present research relating to moose-vehicle collisions. The specific objectives of my research were to i) determine if the MVC mitigation strategy of cutting roadside vegetation attracts moose into roadside areas to browse on vegetation regrowth, ii) identify MVC hotspots and create descriptive maps of these areas in Newfoundland, and iii) determine the environmental features that are correlated with moose-vehicle collision locations on the island. While my case study is on moose-vehicle collisions on the island of Newfoundland, my findings are relevant to other jurisdictions managing ungulate-vehicle collisions.

1.5 Thesis Overview

In Chapter 2, I examined the effect that a common MVC mitigation strategy – roadside vegetation cutting – had on the amount of moose browse occurring in roadside areas. The vegetation within 10-20m of most major roads in Newfoundland is regularly cut, on an as needed rather than scheduled basis. Roadside vegetation cutting is done to increase road safety by increasing driver visibility, but it may actually be attracting moose to roadside areas to browse on vegetation regrowth, perhaps partly due to its high nutritional content (Hughes & Fahey, 1991). I designed a field-based study to compare the intensity of moose browse in roadside areas that were recently cut (2008-2013) to control areas that had not been cut since at least 2008. Counter to my expectation, I found that moose browse is reduced in cut roadside treatment areas compared to the uncut roadside control areas. The results of this chapter could be used by management officials to develop an effective temporal schedule for cutting roadside vegetation.

In Chapter 3, I used kernel density estimation implemented in a Geographic Information System to determine hotspots for MVCs. This analysis revealed MVC hotspots at local, regional, and island extents and these hotspots may serve as key areas for the implementation of mitigation strategies. Additionally, using Geographic

Information Systems and model selection I determined the environmental features that provide the most parsimonious explanation for the probability of MVCs on the island of Newfoundland. Disturbance or road based features such as road classification, road tortuosity, distance to mining areas, and distance to St. John’s were the key variables influencing the probably of MVC occurrence. Results of this chapter could be used by road engineers when designing and building new road networks on the island to avoid areas or road designs with an increased risk for MVCs. This information would also be useful for management officials, tasked with implementing mitigation strategies in strategic locations to reduce the number of MVCs.

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1.7 Figures

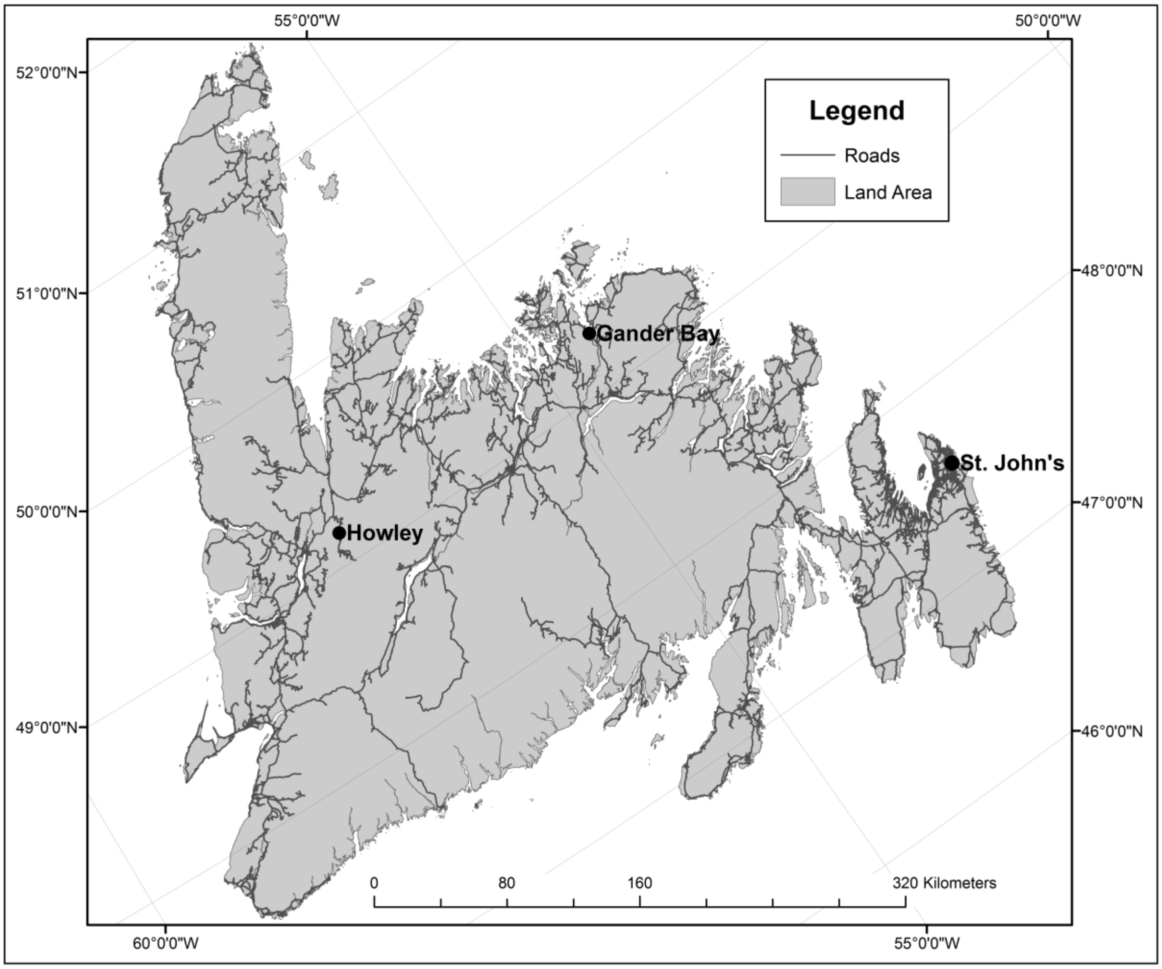

Figure 1-1: Map of the island of Newfoundland, which contains the study areas used in chapters two and three (please refer to Fig. 2-1 and Fig. 3-1 for specific maps of the individual study areas for each chapter). Field sites for chapter two were located in central and eastern portions of the island. This map indicates the provincial capital of St. John's and the two moose introduction locations of Gander Bay and Howley.

1.8 Co-authorship Statement

All manuscripts within this thesis were co-authored with Dr. Shawn Leroux. Chapter 3, Road Characteristics Best Predict Vehicle Collisions with a Non-native, Hyperabundant Ungulate, has additionally been co-authored with Paul Saunders. For all chapters, I was the principal contributor (>50%) for project design, data collection, field research, data analysis, and manuscript preparation. Finally, chapter 2 has been published in the scientific journal *PLoS ONE* (doi:10.1371/journal.pone.0133155) and chapter 3 is in preparation for submission to the *Journal of Wildlife Management*.

CHAPTER 2

Effect of Roadside Vegetation Cutting on Moose Browsing

2.1 Abstract

Moose (*Alces americanus* syn. *A. alces*) vehicle collisions (MVCs) are an issue throughout the range of moose. Many mitigation strategies have been tested and implemented to reduce the number of MVCs, but there have been few empirical analyses of the effectiveness of roadside vegetation cutting. The goal of this study was to determine if roadside vegetation cutting attracted moose to roadside areas to browse on vegetation regrowth. Due to previous studies indicating that moose prefer to feed on plant regrowth, we hypothesized that moose would be attracted to roadside areas with cut vegetation. Consequently, we predicted that there would be higher levels of browsing in cut areas compared to uncut areas. To determine if moose were browsing more in cut or uncut areas, we measured the number of plants browsed by moose in paired treatment (cut on or after 2008) and control (not cut since at least 2008) sites, along with a suite of potential environmental covariates. Using a model selection approach, we fit generalized linear mixed-effects models to determine the most parsimonious set of environmental variables to explain variation in the proportion of moose browse among sites. In contrast to our hypothesis, our results demonstrate that the proportion of moose browse in the uncut control areas was significantly higher than in the cut treatment areas. The results of this study suggest that recently cut roadside areas (7 years or less based on our work) may create a less attractive foraging habitat for moose. The majority of the variance in the proportion of moose browse among sites was explained by treatment type and nested plot number within site identification (34.16%), with additional variance explained by traffic region (5.00%) and moose density (4.35%). Based on our study, we recommend that

vegetation cutting be continued in roadside areas in Newfoundland as recently cut areas may be less attractive browsing sites for moose.

2.2 Introduction

Wildlife-vehicle collisions are a significant problem in many areas of the world, including the United States, Canada, and Europe (Conover, Pitt, Kessler, DuBow, & Sanborn, 1995; Groot Bruinderink & Hazebroek, 1996; L-P Tardif and Associates Inc, 2003). As more roads and infrastructure are constructed, natural connectivity of ecosystems is reduced, leading to wildlife-vehicle encounters. Large ungulates are one of the most problematic species groups involved in wildlife-vehicle collisions. The population size of ungulates in many areas is quite high, with over 1.1 million moose (McLaren, Mahoney, Porter, & Oosenbrug, 2000) and 28.5 million white-tailed deer (Crête & Daigle, 1999) in North America alone. These large population sizes, paired with an expanding road network, increase the likelihood of ungulates being near roads and therefore being involved in wildlife-vehicle collisions. The primary issues associated with a high ungulate population and collisions with vehicles are injuries to humans (or loss of life) and damage to property resulting from the large physical size of ungulates. High levels of wildlife-vehicle collisions, particularly ungulate-vehicle collisions, cause a concern for the public's safety, prompting the implementation of mitigation strategies to reduce the number of collisions (Huijser, Duffield, Clevenger, Ament, & McGowen, 2009).

Numerous different mitigation strategies have been designed and implemented in an attempt to reduce the number of wildlife-vehicle collisions around the world (see review in Huijser et al. (2009)). Common mitigation strategies include physical barriers, deterrents, and public awareness programs. Physical barriers, such as fences along the edge of the highway, seek to preclude access to the roadway (Clevenger, Chruszcz, & Gunson, 2001; Feldhamer, Gates, Harman, Loranger, & Dixon, 1986). Deterrents, such as warning reflectors, seek to make crossing the road undesirable for wildlife (Reeve & Anderson, 1993; Schafer & Penland, 1985; Ujvári, Baagoe, & Madsen, 1998). Public awareness programs, such as wildlife crossing signs (Pojar, Prosence, Reed, & Woodard, 1975; Sullivan, Williams, Messmer, Hellinga, & Kyrychenko, 2004) and cutting of roadside vegetation (Rea, 2003), inform drivers about the increased risk for wildlife in certain area. Each mitigation strategy has pros and cons and different strategies are more likely to be successful under different conditions. Wildlife fencing, for example, has reduced wildlife-vehicle collisions in many areas because it prevents wildlife from trying to cross the road (Clevenger et al., 2001; Dodd, Gagnon, Boe, Manzo, & Schweinsburg, 2007). However, in addition to wildlife fencing being an expensive mitigation strategy, it has further negative consequences such as trapping animals within the fenced area, and acting as a barrier to animal movement, consequently reducing gene flow across landscapes (Huijser et al., 2008; Olsson & Widen, 2008). It is therefore important to conduct both research and monitoring on different mitigation strategies to determine which are the most effective in specific environments. While many mitigation strategies have been widely studied, one common mitigation strategy, roadside vegetation cutting, which involves clearing or cutting vegetation along roadsides to improve driver visibility of animals near roads (AMEC Earth & Environmental, 2004; Child, 1998; Rea, Child, Spata, & MacDonald, 2010) (also referred to as roadside brush cutting), has had little empirical analysis. This project was designed to be a first step to investigate whether cutting of roadside vegetation attracted moose to roadside areas in Newfoundland, Canada to browse on vegetation regrowth.

Roadside vegetation is being cut in Newfoundland and in many other areas across Canada, allowing drivers an opportunity to see wildlife in the roadside areas and adjust their driving to avoid collisions (Beckmann, Clevenger, Huijser, Hilty, & Forman, 2010). However, roadside vegetation cutting could have unintended consequences because while it increases driver visibility, cutting may actually be attracting moose to roadside areas to forage on the new vegetation growth (Rea, 2003). Continual cutting of roadside vegetation prevents forest succession from occurring (Rea, 2003), which leaves the ecosystem in an early successional state and may provide optimal moose foraging habitat (Franzmann, 1978).

The goal of this study is to determine if roadside vegetation cutting attracts moose into roadside areas to browse on the vegetation regrowth. Hughes and Fahey (1991) indicate that ungulates prefer to feed on plant regrowth for at least the first three years after cutting, or new plant growth, due to its high nutritional content. If roadside vegetation regrew with suitable forage for moose, then we expect moose to spend more time near roads, and consequently pose a higher risk for moose-vehicle collisions (MVCs). Specifically, we hypothesize that moose are attracted to roadside areas with cut vegetation rather than to areas where no vegetation cutting has occurred in at least the past seven years (based on access to roadside vegetation cutting data). Consequently, we predict that there will be higher levels of browsing in cut areas compared to uncut areas.

We test this hypothesis by comparing the amount of moose browse in areas where roadside vegetation has been recently cut to areas where it has not been recently cut.

2.3 Study Area

Newfoundland is an island in the North Atlantic Ocean that falls within the boreal forest region. The study was conducted from June 17th to July 23rd 2014 along roadsides in two ecoregions in Newfoundland, Canada: maritime barrens and central Newfoundland forest. The sites in the maritime barrens region, on the Avalon Peninsula, were La Manche Provincial Park (MAN), Renews-Cappahayden (REN), and Spaniard's Bay (SPA) (Fig. 2-1). The region is dominated by black spruce (*Picea mariana*), balsam fir (*Abies balsamea*), tamarack (*Larix laricina*) and many shrub and lichen species, with a mean annual precipitation of 1,400mm and temperature of 5.5°C (Bell, 2002b). The sites in the central Newfoundland forest region were Badger (BAD), Grand Falls-Windsor (GFW), and Gander Bay (GAN) (Fig. 2-1). The region is dominated by black spruce, balsam fir, paper birch (*Betula papyrifera*), trembling aspen (*Populus tremuloides*), and sheep laurel (*Kalmia angustifolia*), with a mean annual precipitation of 1,150mm and temperature of 4.5°C (Bell, 2002a).

2.4 Methods

2.4.1 Site Selection

All vegetation adjacent to the road in Newfoundland is cut back approximately 20m along main roads, such as the Trans-Canada Highway (TCH). We paired treatment sites with nearby control sites that had similar biophysical traits (i.e., no herbicide use after 2009, elevation, road speed limit, vegetation cut widths, traffic volumes, and moose densities), but differed in the age of cut vegetation (Table 2-1, A1-1 and A1-2 Tables). We obtained data from the Department of Transportation and Works for roadside vegetation cutting projects issued by the Government of Newfoundland and Labrador from 2008 to 2013 and herbicide application projects from 2010 to 2013. Herbicide application and vegetation cutting data were unavailable for the paired control sites (hereafter controls) prior to 2010 and 2008 respectively. We selected secondary roads for our sampling due to the high traffic volume and associated risk of sampling beside a busy highway. For this study, secondary roads are roads that are not the Trans-Canada Highway, generally having lower traffic volume and traffic speed (≤80km/h) than the Trans-Canada Highway. In 2012, 58% of MVCs occurred on secondary roads, making secondary road sampling suitable for our study. The side of the road to be sampled was randomly selected except if there was additional infrastructure making one side unsuitable for our study (e.g., power lines).

2.4.2 Data Collection

We used a stratified random sampling grid to measure the number of plants browsed by moose per plot in roadside areas with cut vegetation and in nearby control areas (Hurlbert, 1984). A 45m long grid was laid out parallel to the roadway and subset into 9 5-m sections. The width of the sampling grid was determined by the width of the roadside vegetation cut area at each site (sites ranged in size from 45m*11m to 45m*16m). We divided the width into 3 equal sections, giving us 27 potential plots to sample per grid. We randomly selected 9 plots, one in each 5-m section, making sure to avoid having spatially adjacent plots (Fig. 2-2). We sampled vegetation in a 9-m^2 quadrat placed in the center of each of the 9 plots per site.

To determine the amount of moose browse, we measured a series of plant traits in each 9-m^2 quadrat. An overall percent ground cover was visually estimated for each site. Woody plants within the 9-m^2 quadrats were identified to species. Evidence of moose browse is readily detectable on woody plants (Frerker, Sonnier, & Waller, 2013); allowing us to record whether or not the woody plant had been browsed by moose (i.e., we measured moose browse as a binary response – browsed or not browsed). We also recorded the height of each plant in our plots. We collected data on road speed limit, presence of water bodies within the site, and the topographic gradient of the site.

The response variable in this analysis was the proportion of moose browsed plants per plot measured as (the number of browsed plants/ the total number of browsable plants per plot) on an annual scale. We considered plants that were browsed at least once by moose in the entire study as browsable. We measured a series of discrete and continuous variables that may influence moose browse along roadsides. The discrete explanatory variables were: treatment type, presence or absence of water bodies, and traffic region (Table A1-3). Treatment type was a categorical variable with three levels; control (not cut since at least 2008), treatment 1 (cut between 2008-2010, 2 sites from 2009 and 1 from 2010), and treatment 2 (cut between 2011-2013, 2 sites from 2011 and 1 from 2013). Presence or absence of water bodies was determined visually within each site during sampling, and we split the study sites into two traffic regions based on the difference in average daily traffic, i.e., the Avalon and central Newfoundland. The Avalon Peninsula is located on the south-eastern edge of Newfoundland and contains the capital of St. John's (Fig. 2-1). Traffic counters deployed at our sites from June 11th to July 1st 2014 indicated that sites on the Avalon Peninsula experienced much higher traffic volumes (mean ±SD number of vehicles per day: 1,889 ±275) than sites in central Newfoundland (mean ±SD number of vehicles per day: 670 ±242).

We included six continuous explanatory variables for variation in the proportion of browsed plants along roadsides: the width of the site, gradient up to the roadside, gradient up to the tree-side, road speed limit, moose density, and plant preference index (Table A1-3). Width of the site was measured in the center of the site, from where continuous vegetation started closest to the road up to the edge of the tree line. The gradient up to the roadside was measured as the mean slope of the site from the bottom of the site towards the road from points taken on either end and in the center of the site. The gradient up to the tree-side was measured in a similar manner as the gradient up to the roadside except it was measured from the bottom of the site and toward the trees. Road speed limit was determined using the posted speed limit signs on each road. Moose density was calculated for each moose management area using a stratified-random block aerial survey design, conducted by the Department of Environment and Conservation –

Wildlife Division (Gosse, McLaren, & Eberhardt, 2002). Each moose management area is stratified and all moose and tracks recorded, then blocks are assigned to low, medium, or high moose density categories. A sightability correction factor is then applied to each category based on land cover and topography of the survey area. Different moose management areas are surveyed every year with an effort being made to have at least one moose management area in each of the island ecoregions surveyed per year.

2.4.3 Statistical Analysis

2.4.3.1 Moose Plant Preference

We attempted to control for differences in plant "quality" or preference across sites by selecting control areas close to the treatment areas. While many plants may be only occasionally browsed, preferred species are consumed in a larger proportion than their availability in the environment (Renecker & Schwartz, 1998). Most other studies present a list of plant species that they deem to be preferred or high quality without any justification of the distinction between preferred and non-preferred species (e.g., Cumming, 1987; Eldegard, Lyngved, & Hjeljord, 2012; Routledge & Roese, 2004). We used our browse data to define what is considered a preferred resource for Newfoundland moose. Plants that were browsed at least once by moose in the entire study were used in the analysis to determine the proportion of browsable plants browsed, with the proportion calculated as (the number of browsed plants of species i/ the total number of plants of species i). Then, to identify a potential preference or quality threshold in plant species used by moose in Newfoundland, we applied segmented regression (segmented package in R v.3.0.1 Muggeo, 2008) to the frequency of the plants that were browsed at least once by moose in our study. The segmented regression identified a threshold in browse frequency whereby plants above the threshold are browsed more frequently than plants below the threshold. We considered plants above this threshold as preferred moose browse. The quality of each site, determined via the plant preference index, was then calculated as (the number of preferred plants per plot/ the total number of plants per plot) (Fig. A1-4).

2.4.3.2 Model Selection for Proportion of Browsed Plants by Moose

Using a model selection approach, we built generalized linear mixed-effects models with a hierarchical structure, containing a logit canonical link, and a binomial error structure. We included plots nested within sites as random variables in all of our models to account for the hierarchical structure of our sampling and our paired treatment-control site design. We also included sites as a grouping variable to account for some of the variation in plant presence among sites. Proportion of browsed plants was the dependent variable and we had a suite of three discrete and six continuous explanatory variables (Table A1-3). As explanatory variables that are highly correlated with each other should not be included in the same model, we conducted both Pearson's and Spearman's correlation analyses to determine which explanatory variables to include as fixed effects in our models (Table A1-5). Since the main goal of the study was to investigate whether vegetation cutting altered the proportion of plants browsed by moose, we decided a priori to include treatment type as an explanatory variable in all of the potential models. The only variables not highly correlated with treatment type, and therefore the only other variables included in our models, were traffic region, width of site, and moose density. Treatment type was significantly correlated with site quality, with control sites having higher browse quality than cut sites (*rho*=−0.30, S=272145.8, *P*=0.002) (Fig. A1-6). Because these variables are correlated, we are unable to determine the relative importance of treatment type versus site quality in explaining variation in moose browse along roadsides. However, we fit generalized linear mixed-effects models of proportion of moose browse and treatment type, and proportion of moose browse and site quality (based on the plant preference index) to determine which variable explained the most variance in the proportion of moose browse occurring in roadside areas. Additionally, we included a weighted vector of the number of plants per plot to account for the differences in the number of plants among plots. We used the glmer function within the lme4 package (Bates, Mächler, Bolker, & Walker, Submitted June 2014) in R v.3.0.1 for all of our analysis. The R code and associated data are available on figshare (Tanner & Leroux, 2015).

We used Akaike Information Criterion corrected for small sample size (AIC_c) to determine the most parsimonious models out of all of the competing models. We considered any model with a $\Delta AIC_c<2$ as a parsimonious model (Burnham & Anderson, 2002). We calculated the amount of variance explained by each variable by calculating the improvement in the marginal R^2 value when these additional variables were added to the basic model. Width was a potential variable that was included in the original model set, but was a pretending variable (sensu Anderson (2008)) and therefore the two models containing width were removed. Pretending variables do not explain additional variation in the model but their inclusion in the candidate set of models can erroneously increase model selection uncertainty (Anderson, 2008).

2.5 Results

2.5.1 Moose Plant Preference

Of the 32 plant species that showed at least one occurrence of moose browse in the study, 18 species show very low frequency of moose browse (mean = 1.74%, range = 0.05% to 4.76% of individual plants were browsed) and 14 species showed relatively high frequency of moose browse (mean = 37.14%, range = 7.43% to 72.73% of individual plants were browsed) (Fig. 2-3). Our segmented regression of browse frequency identified a single threshold (i.e., a shift in frequency of moose browse) in the proportion of moose browse at 4.76% browse (Fig. 2-3). Consequently, we considered plants with more than 4.76% browse to be preferred plants for moose. In terms of abundance, wild red raspberry (*Rubus idaeus*) is abundant (n=2954) but rarely selected when present, while trembling aspen is scarce (n=13) but often selected when present (Fig. 2-3).

2.5.2 Model Selection for Proportion of Browsed Plants by Moose

The candidate set of models consisted of four models, with three of the models having ΔAIC_c values of <2 and ωAIC_c between 0.26 and 0.38 (Table 2-2), indicating that they were parsimonious models for explaining variation in the proportion of moose browse in roadside areas. These top models included the fixed effects: treatment type, traffic region, and moose density, and the nested random effects: site identification and plot number (Table 2-2). These models explained between 34% and 39% of the variation in the proportion of moose browse in roadside areas. Our basic model consisted of treatment type and plot number nested within site identification, which explained the majority of the variance (34.16%, Table 2-2) in the proportion of moose browse among sites. Traffic region (5.00%, Table 2-2) and moose density (4.35%, Table 2-2) explained a much lower amount of variance in the proportion of moose browse among sites. A comparison of models with either treatment type or plant preference showed that treatment type (ωAICc = 1.00) was the explanatory variable that explained the most variation in moose browse along roadsides when compared to preferred species (ωAIC_c = 0.00) (Table A1-7). Treatment type, traffic region, and moose density were all negatively correlated with the proportion of moose browse in roadside areas (Table 2-3). We compared treatment and control sites to determine if control areas had more preferred plants (based on Dodds 1960), resulting in more browse occurring in the control rather than treatment sites. We found that visually, depending on the species of plant, control and treatment areas were fairly evenly matched in terms of the number of preferred plants present (Fig. A1-8).

The proportion of moose browse in the control areas was 5.67 times higher than the proportion of moose browse in the 2008-2010 cut treatment areas and it was considerably higher than proportion of browse in the 2011-2013 cut treatment areas (Fig. 2-4). The proportion of moose browse in the 2008-2010 cut treatment areas was also higher than the proportion of browse in the 2011-2013 cut treatment areas (Fig. 2-4). The percent of vegetation within 3 different height categories (<30cm, 30-200cm, and >200cm) was found to be comparable between both treatment and control sites (Table A1-9).

2.6 Discussion

Roadside cutting is often used as a method to improve visibility of moose on the sides of roadways, but it may have unintended consequences if cut areas act as an attractant for moose. Even though our study only contained six paired treatment-control sites, the effect size of roadside vegetation cutting on moose browsing was very large. Specifically, the proportion of plants browsed by moose in the control sites was on average 1.5 to 23.2 times higher than in the two treatment areas – this despite the sites having similar vegetation communities. These results, which are in contrast to our initial hypothesis, thereby suggest that recently cut areas may not act as attractants for moose to browse.

Child, Barry, and Aitken (1991) suggested that management of roadside vegetation creates favourable habitats for moose by maintaining early seral vegetation. Additionally, Rea (2003) suggested that roadside vegetation cutting could unintentionally stimulate plant regrowth that is more nutritious, ultimately increasing the attractiveness of the area for moose foraging, and consequently increasing the likelihood of MVCs. However, contrary to our hypothesis based on previous work, we found evidence of more moose browse in control areas – not cut since at least 2008 – than in treatment areas. We also found that cutting treatment best explained the variance in the proportion of moose browse among sites (Table 2-2, Fig. 2-4). These results indicate that roadside vegetation cutting does play a large role in the amount of moose browse occurring in roadside areas, which could have a direct effect on the number of MVCs. We have not, however, investigated the effect of roadside vegetation cutting on the number of MVCs directly.

Nevertheless, since our results are contrary to Rea (2003), it follows that if roadside areas are less attractive to moose, then the likelihood of MVCs should decrease within cut areas especially since cutting is also performed to increase driver visibility (Bashore, Tzilkowski, & Bellis, 1985; Del Frate & Spraker, 1991; Rea, Child, Spata, & MacDonald, 2010). Work by and Andreassen, Gundersen, and Storaas (2005) and Jaren, Andersen, Ulleberg, Pedersen, and Wiseth (1991) indicated that cutting vegetation along railways resulted in a 40% to 56% decrease in the number of moose-train collisions, respectively. Cutting of vegetation appears to be a successful mitigation strategy to reduce moose-train collisions in Norway and future studies can build on this and our work to determine if it is a successful mitigation strategy for other vehicle types in other locations.

The species and availability of plants in roadside areas will be a key determinant of moose browse potential (Table A1-3). Many studies have independently determined preferred or high quality species for moose to browse on (Cumming, 1987; Dodds, 1960; Routledge & Roese, 2004), but the species on the lists vary and there are no quick methods to differentiate preferred from non-preferred species. We were interested in identifying the types of species that moose forage on in roadside areas. Consequently, we developed a surrogate technique to rapidly determine plant species that are preferred by moose in place of more detailed and specific methods such as Dodds (1960). A clear threshold existed in our data where certain plant species could be considered frequently used resources for moose along secondary roads in Newfoundland (Fig. 2-3). Dodds (1960) determined the percent use of plants by moose in Newfoundland by examining the number of stems browsed by moose. Our method is far less time consuming as it only considers if the plant has been browsed by moose or not, rather than counting individual stems. The analysis provided consistent results for preferred or high quality browse species with respect to Dodds (1960), as 12 of the 14 species determined to be preferred by our calculations were also included on Dodds' list. We believe our threshold approach will be useful in other studies attempting to quantify resource quality from plot to landscape level, and will significantly reduce the sampling time required to identify similar species that are deemed preferred forage species by other more time consuming techniques.

Moose density also explained a small amount of the variance in moose browse along roadsides (Table 2-2). We included moose density because we hypothesized that it would play a role in the proportion of moose browse occurring. However, our model predicts that the proportion of roadside moose browse will decline with increasing moose densities (Table 2-3). This is contrary to our expectation and it may be explained by the fact that the measure of moose density was too coarse (moose management areas within Newfoundland) to capture small scale variation in moose densities around secondary roads. An alternative explanation would be that areas with high moose density provide sufficient food and allow a large population of moose to thrive in the area without having to frequent roadside areas to browse. Additionally, traffic region (Avalon or central Newfoundland) also explained a small portion of the variation in moose browse along roadside (Table 2-2). The model including traffic region predicts that the proportion of moose browse occurring in roadside areas will be lower in areas with more traffic (i.e., Avalon) (Table 2-3). Moose may avoid areas with higher traffic volume or reduce their crossing rates in regions with high traffic volume (Dussault et al., 2007; Eldegard, Lyngved, & Hjeljord, 2012; Laurian et al., 2008).

Our correlational field study has low inferential strength, but it does provide a new line of evidence about roadside vegetation cutting and its effect on moose browsing. Our study could be improved by having true control areas that had never been cut and by having more treatment and control sites overall to increase the strength of our inference. Our data, however, does clearly indicate that roadside vegetation cutting of secondary roads in Newfoundland does not attract moose to roadside areas to browse on plant regrowth as previously suggested (Child et al., 1991; Rea, 2003). Although moose may have had longer to browse in control than treatment areas, moose browsed plants likely cannot be conclusively identified as browse rather than a broken branch after about two years. Therefore, it is unlikely that the variation in time frame would result in such a large effect size when comparing the amount of browse in cut versus uncut sites. Future studies could examine the direct links between roadside vegetation cutting and the probability of MVCs. This could be achieved by building on Joyce and Mahoney's (2001) large-scale spatial analysis of the determinants of MVCs. A revised analysis would make use of new georeferenced MVC data for the island of Newfoundland that were not available before 2012.

2.7 Management Implications

We provided the first line of evidence that recently cut roadside areas may not be attractive browse areas for moose. Based on our study we recommend that vegetation cutting be continued in roadside areas to both increase driver visibility and to reduce the attractiveness of the area for moose to browse. In our case, sites cut between 1 to 7 years of our sampling had lower moose browse than control areas which suggests that a regime of frequent roadside cutting may help mitigate moose browse along roadsides. Additionally, our surrogate technique for determining preferred forage species will save considerable time in the field and can be applied to studies of ungulate browsing conducted outside of Newfoundland. The main issue of reduction of MVCs in Newfoundland will not, however, be achieved through the implementation of one mitigation strategy. We do not have data to speak beyond roadside clearing as a mitigation strategy but based on other work (Huijser et al., 2009; Knapp & Whitte, 2006), a comprehensive MVC reduction program should evaluate all possible strategies and the costs and benefits of each. In the end, a mitigation strategy that works in one area may not work in another due to multiple extenuating factors, including the physical landscape or general ecosystem structure. For example, underpasses were implemented in Alberta in combination with fences and resulted in substantial reductions in wildlife-vehicle collisions (Clevenger et al., 2001), but this strategy may not be feasible for many regions due to the bedrock being extremely close to the surface. All mitigation strategies adopted should be studied within an adaptive management framework (Walters, 1986), where the effectiveness of the strategy is carefully monitored and the strategies can be modified over time based on their “success”.

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2.1 Figures

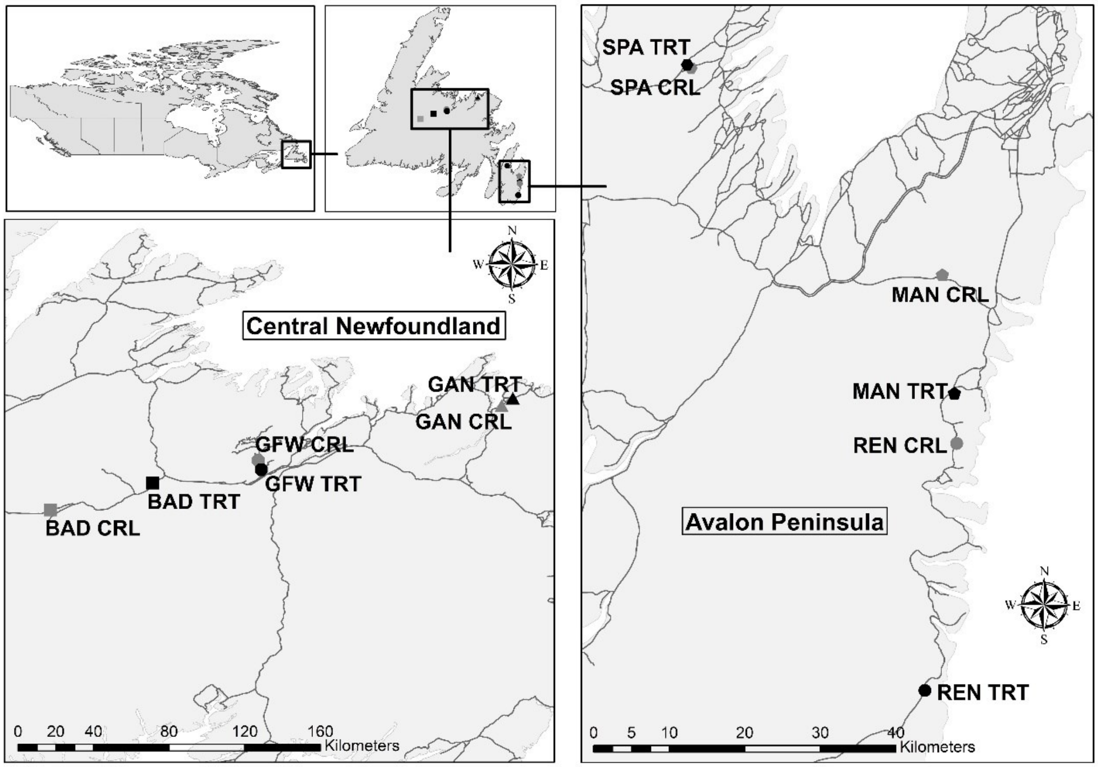

Figure 2-1: The locations of the paired treatment (TRT, black points) and control (CRL, grey points) locations used in our study in Newfoundland, Canada. The linear grey features are roads. Vegetation and evidence of moose browse at the sites was sampled from June 17th – July 23rd 2014. Locations; BAD: Badger, GFW: Grand Falls-Windsor, GAN: Gander Bay, MAN: La Manche Provincial Park, REN: Renews-Cappahayden, and SPA: Spaniards Bay. Treatment 1: BAD, GFW, REN, and Treatment 2: GAN, MAN, SPA.

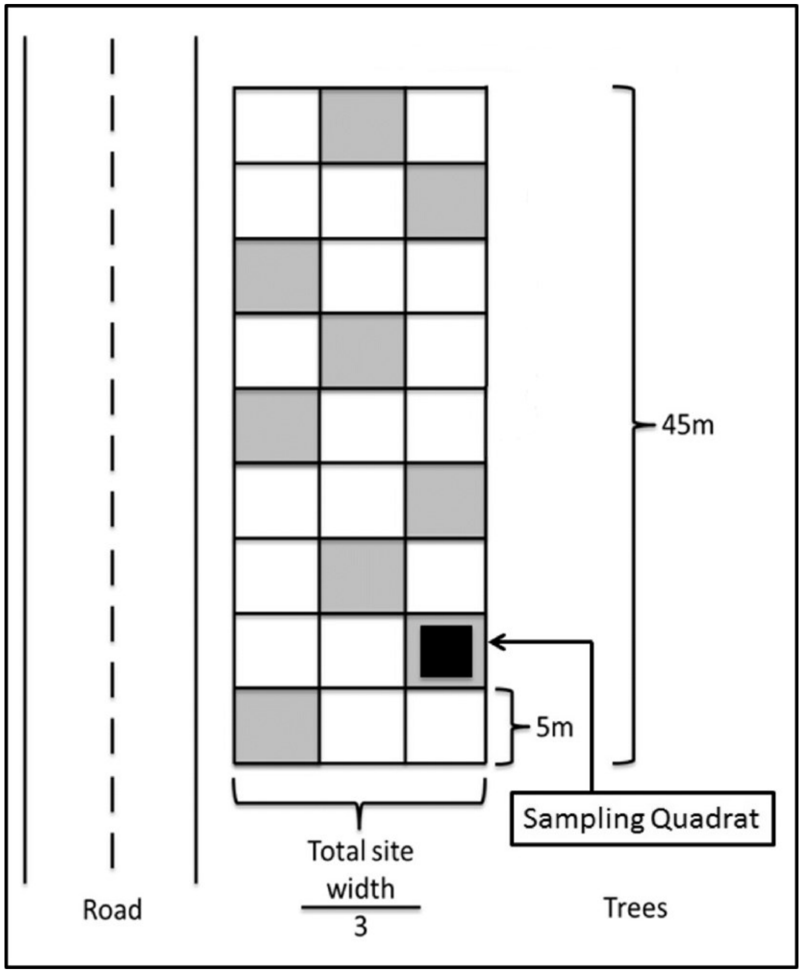

Figure 2-2: Schematic of sampling grid used to select sampling plots within sites for quantifying the proportion of plants browsed by moose in Newfoundland, Canada. We used stratified random sampling and the grey boxes represent one potential set of plots sampled at a site. The total width of the site was divided by three to ensure that there were three rows of sampling. The black box represents the 9-m^2 quadrat that was sampled within each of the grey plots.

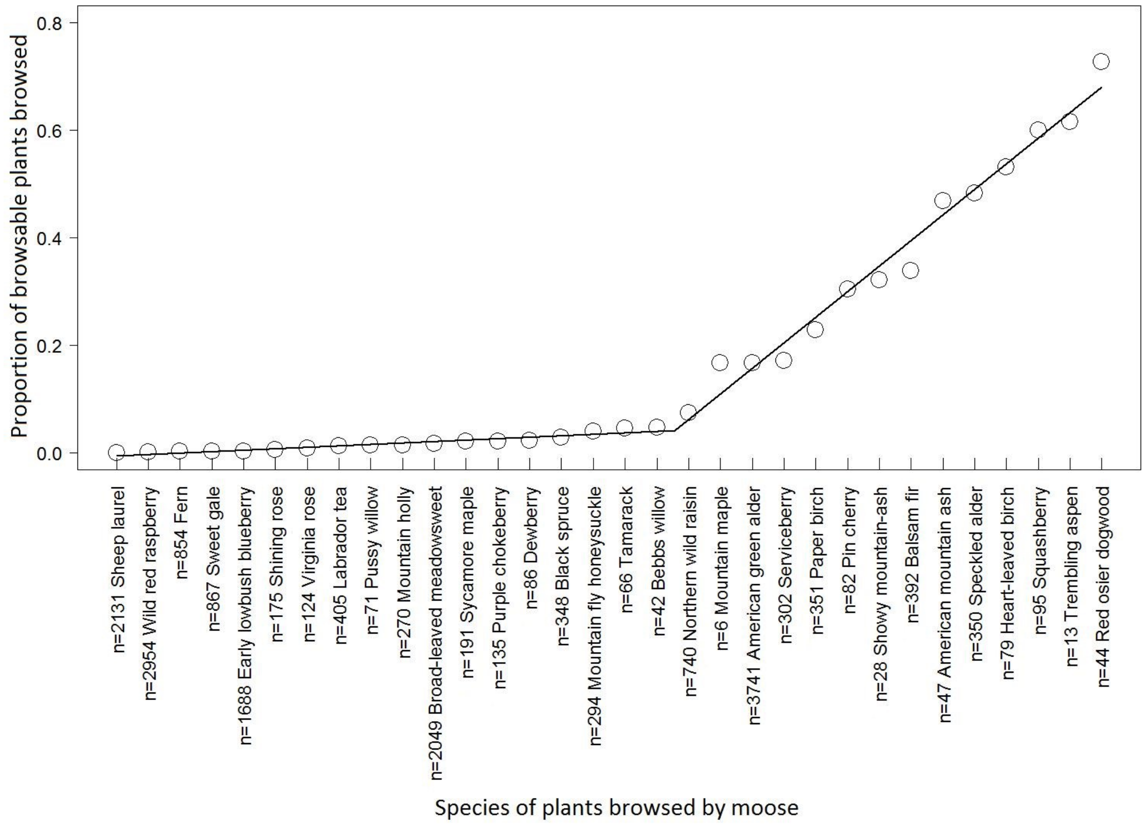

Figure 2-3: Segmented regression analysis used to determine preferred plant species for moose within the entire study. The proportion of browsable plants browsed was determined using plants that were browsed at least once by moose in the entire study and then calculated as (the number of browsed plants of species i/ the total number of plants of species i). The threshold occurs after Bebb's willow (*Salix bebbiana*), indicating that all plants from northern wild raisin (*Viburnum nudum*) through red osier dogwood (*Cornus stolonifera*) are considered preferred forage species for moose in our study area. The n value before each plant name indicates the total number of individuals in all plots. Equation and R^2 for each line segment (line 1: $y=0.0027x-0.0082$, R^2=0.91; line 2: $y=0.0475x-0.8398$, R^2=0.98).

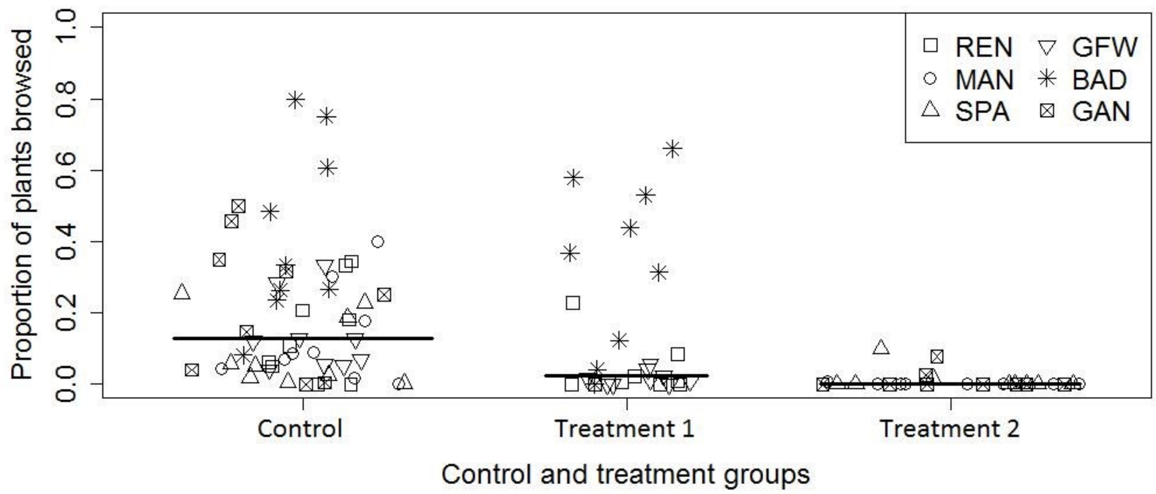

Figure 2-4: The proportion of plants browsed by moose in all of the control sites (Control) vs all of the treatment sites cut from 2008-2010 (Treatment 1) vs all of the treatment sites cut from 2011-2013 (Treatment 2). Each point represents data from a single plot. The solid black lines represent the median proportion of browsed plants in each of the control (median=0.13), treatment 1 (median=0.02), and treatment 2 (median=0.00) groups. For the locations; BAD: Badger, GFW: Grand Falls-Windsor, GAN: Gander Bay, MAN: La Manche Provincial Park, REN: Renews-Cappahayden, and SPA: Spaniards Bay. Treatment 1: BAD, GFW, REN, and Treatment 2: GAN, MAN, SPA.

2.2 Tables

Table 2-1: Descriptive statistics for the explanatory variables included in the correlation analysis of the proportion of moose browsed plants in roadside areas. Data were collected from June 17th – July 23rd 2014 from roadside sampling locations in Newfoundland, Canada.

Variable	Description	Treatment Type					
		Control		2008-2010 Cut		2011-2013 Cut	
		Mean	SD	Mean	SD	Mean	SD
Water bodies	Presence or absence of water bodies (0=no water) (1=yes water)	0.17	±0.38	0.67	±0.48	0.67	±0.48
Width	Width of site (m)	14.17	±1.56	15.07	±1.01	13.27	±1.50
Road speed	Road speed limit (km/h)	71.67	±12.25	70.00	±14.41	80.00	±0.00
Gradient road	Gradient up to roadside (cm)	0.43	±0.15	0.49	±0.05	0.62	±0.06
Gradient tree	Gradient up to tree-side (cm)	0.31	±0.25	0.05	±0.07	0.15	±0.22
Traffic region	Traffic region (0=Avalon) (1=Central Newfoundland)	0.50	±0.50	0.33	±0.48	0.67	±0.48
Moose density	Moose density (# moose/ km^2)	2.16	±1.09	2.21	±1.09	2.10	±1.12
Elevation	Elevation (m)	106.50	±60.19	86.00	±32.68	70.33	±27.22
Proportion of preferred plants	Plant preference index (# of preferred plants per plot/ total # of plants per plot)	0.51	±0.32	0.34	±0.25	0.31	±0.27

Table 2-2: Four generalized linear mixed-effects models included in model selection to determine which environmental explanatory variables influenced the proportion of moose browsed plants along roadsides. The variables plot number nested within site id were included as random effects in all models. We used an intercept only model as the null model to ascertain if adding additional fixed effects improved the AIC_c.

Model[a]	Description	k[b]	LL[b]	AIC_c[b]	ΔAIC_c[b]	ωAIC_c[b]	Marginal R^{2b}	Conditional R^{2b}
1	treatment type+ moose density	6	−336.93	685.86	0.00	0.38	0.39	0.43
2	treatment type+ traffic region	6	−337.01	686.03	0.16	0.35	0.39	0.44
3	treatment type	5	−338.32	686.65	0.78	0.26	0.34	0.42
4	Null model	3	−371.17	748.35	62.48	0.00	0.00	0.15

[a] Models are ranked with Akaike Information Criterion, corrected for small sample size (AIC_c)

[b] Key: k, number of parameters; LL, log-likelihood; AIC_c, Akaike Information Criterion, corrected for small sample size; ΔAIC_c, the difference in the AIC_c; ωAIC_c, models weights; Marginal R^2, Nakagawa and Schielzeth's Marginal R^2 which is the proportion of variance explained by the fixed factors alone; Conditional R^2, Nakagawa and Schielzeth's Conditional R^2 which is the proportion of variance explained by both the fixed and random factors.

Table 2-3: Results of the four generalized linear mixed-effects models used to determine which variables influenced the proportion of moose browse within the treatment and control sites in Newfoundland, Canada.

Fixed Effect	Parameter Estimates	
	Estimate	95% CI
Model 1: proportion browsed plants ~ treatment type + moose density		
Intercept (control)	-0.84	
Treatment type (2008-2010)	-1.58	-2.54, -0.61
Treatment type (2011-2013)	-4.77	-6.03, -3.51
Moose density	-0.59	-1.20, 0.01
Model 2: proportion browsed plants ~ treatment type + traffic region		
Intercept (control)	-1.48	
Treatment type (2008-2010)	-1.68	-2.63, -0.74
Treatment type (2011-2013)	-4.63	-5.86, -3.41
Traffic region (Yes: on Avalon)	-1.25	-2.62, 0.12
Model 3: proportion browsed plants ~ treatment type		
Intercept (control)	-2.10	
Treatment type (2008-2010)	-1.67	-2.62, -0.71
Treatment type (2011-2013)	-4.67	-5.91, -3.43
Model 4: proportion browsed plants ~ 1		
Intercept (control)	-3.57	

CHAPTER 3

Road Characteristics Best Predict Vehicle Collisions with a Non-native, Hyperabundant Ungulate

3.1 Abstract

With roads encroaching into natural environments, there is an increased likelihood of wildlife coming in contact with vehicles, resulting in an increase in wildlife-vehicle collisions. Collisions involving moose (*Alces americanus* syn. *A. alces*) are prevalent in North America, together with the large physical size of moose, these collisions are especially dangerous to vehicle occupants. Many mitigation strategies are being implemented to minimize moose-vehicle collision (MVC) rates. Our goals were to i) create predictive maps to identify hotspots for MVCs in Newfoundland, Canada, and ii) determine what environmental features are correlated with the locations of MVCs on the island. We hypothesized that distance to wetlands, topographic variation, and traffic volume would be the best predictors of MVCs on the island. Non-parametric kernel density estimation identified several local hotspots, and the Avalon Peninsula as a large-scale hotspot for MVCs on the island of Newfoundland. To determine what spatial features best predict MVC locations, we compared environmental variables at known MVC locations to environmental variables at random sites along the Newfoundland road network. We fit generalized linear models to determine the most parsimonious set of environmental variables to explain the probability of occurrence of MVCs. Our results demonstrate that disturbance or road variables are considerably better predictors of MVCs than other environmental variables. The most supported model was a disturbance or road based model that explained ~30% of the variance in the probability of MVC occurrence, with the variables of interest being: road classification, road tortuosity, distance to mining areas, and distance to large developed areas (St. John's – used as a proxy for traffic volume). Based on our analyses, we recommend that mitigation strategies be

implemented on primary roads (such as the Trans-Canada Highway), on straight road sections, and close to areas of high traffic (such as mining areas and large cities) to reduce the frequency of MVCs.

3.2 Introduction

The human population is on the rise around the world, increasing the urbanization of natural areas and requirement for roads, leading to human-wildlife conflicts. Roads have a large effect on ecosystems, not only do they remove habitat, but roads also create a larger proportion of edge area, are sources of chemical and noise pollution, and form a barrier to animal movement (Forman et al., 2003). The creation of roads into historically natural environments leads to an increased likelihood of wildlife coming in contact with vehicles, resulting in a potential increase in wildlife-vehicle collisions (WVCs). Wildlife-vehicle collisions occur with many different species, ranging from small amphibians such as frogs (Farmer & Brooks, 2012) up to larger mammals such as ungulates. Collisions with these larger mammals can cause serious human injuries, and even death (Oosenbrug, Mercer, & Ferguson, 1991). For example, between 2000 and 2010 on the island of Newfoundland (Canada), there were approximately 4,400 MVCs, resulting in 18 human fatalities and 900 injuries (Policy, Planning, and Evaluation Division, 2014).

Vehicle collisions involving moose (*Alces* spp.) are especially dangerous to driver and passenger safety due to the large body size of moose. Such collisions are also financially costly; with the average cost associated with a single moose-vehicle collision (MVC) at ~$30,760 (based on US$ 2007) (Huijser, Duffield, Clevenger, Ament, & McGowen, 2009). Collisions, however, are only required to be reported if there is property damage totalling over $1,000, or human fatality or injury (Transport Canada, 2012). The exact degree of underreporting for WVCs is unknown, but is estimated at approximately 40-50% in Canada (L-P Tardif and Associates, 2003). However, Snow, Porter, and Williams (2015) found that even when simulating a high level of underreporting of ungulate-vehicle collisions, predictive modelling of these locations were still reliable, likely due to the clustered nature of ungulate-vehicle collisions, and therefore should not deter research being conducted with these collision datasets. According to J. M. Sullivan (2011), the number of fatal WVCs in the United States has increased by 104% since 1990. This causes a concern for management officials tasked with implementing mitigation strategies in the most strategic locations to reduce the number of WVCs.

Evidence suggests that wildlife-vehicle collisions along roads are spatially clustered for many species, not only ungulates (Danks & Porter, 2010; Ramp, Caldwell, Edwards, Warton, & Croft, 2005). This spatial clustering indicates "hotspot" locations for WVCs, which are areas where a disproportionately large number of such collisions occur (Litvaitis & Tash, 2008). Due to the increased collision risk, these areas are the most dangerous for both humans and wildlife. As stated by Ramp et al. (2005) it would be extremely costly and logistically impossible to implement mitigation strategies on all sections of roads, therefore hotspots need to be identified. These high-risk areas should be the first to receive the implementation of mitigation strategies to reduce the frequency of WVCs as quickly as possible.

WVC studies throughout Canada (Dussault, Poulin, Courtois, & Ouellet, 2006; Hurley, Rapaport, & Johnson, 2007; Joyce & Mahoney, 2001; Rea, Johnson, & Emmons, 2014), the United States (Danks & Porter, 2010; Snow, Williams, & Porter, 2014), and in areas of Europe (Hothorn, Brandl, & Müller, 2012; Malo, Suarez, & Diez, 2004; Seiler, 2005), have focused on the primary factors contributing to collision locations. A review by Gunson, Mountrakis, & Quackenbush (2011) demonstrated that multiple landscape features are good predictors of WVCs. For example, Dussault et al. (2006) found that increased wildlife density and presence of brackish pools were associated with higher rates of MVCs. Determining what environmental factors are associated with collisions could help develop appropriate mitigation strategies in areas of concern for MVCs in Newfoundland.

We set out to identify areas with high numbers of MVCs and determine what environmental features are correlated to MVC locations in Newfoundland, Canada to help inform ungulate and road management practices on the island. Moose are a highly abundant, non-native, deliberately introduced species in Newfoundland, and the provincial government is actively seeking to implement additional mitigation measures to reduce the number of MVCs. Specifically, our objectives are to i) identify and create predictive maps of MVC hotspots on the island of Newfoundland, and ii) determine what environmental features are associated with the locations of MVCs on the island. Based on the review by Gunson et al. (2011) and the work by Joyce and Mahoney (2001), we hypothesize that distance to wetlands, topographic variation, and traffic volume will be the best predictors of the locations of MVCs in Newfoundland. Specifically, we expect there to be an increase in MVCs the closer you get to wetland areas, as moose are attracted to these area to drink, feed on aquatic plants, and avoid insects (Peek, 1998). We expect there to be an increase in MVCs in areas with low terrain variation since moose may use these flat areas as travel corridors and highly rugged areas may act as impassible features, forcing moose into flatter areas (Dussault et al., 2006; Hurley et al., 2007). Finally, we expect more MVCs to occur in areas with a higher traffic volume as more vehicles increase the likelihood of a collision occurring with a moose (Danks & Porter, 2010; Joyce & Mahoney, 2001).

3.3 Methods

3.3.1 Data

The study area consists of the entire island of Newfoundland, Canada found within the boreal forest region. Moose occur across the entire island and consequently MVC locations were scattered throughout the island area. We obtained georeferenced MVC data for 2012 from the Newfoundland and Labrador Department of Transportation and Works as well as from Terra Nova and Gros Morne National Parks. These data from the Department of Transportation and Works represent collisions resulting in human injury (or fatality) or property damage totalling over $1,000. Our full data set included 640 MVCs across the island of Newfoundland from 2012. This is the first and currently the only available year of georeferenced MVC data for the island of Newfoundland.

From the original data set of 640 MVC locations, we removed 40 points for the following reasons; 11 had no georeferenced location data, 10 were incorrectly georeferenced (i.e., they were in the ocean or waterbodies), 12 were >250m off the road (i.e., more than half of the radius of smallest buffer size off the road – see below for details on buffer analysis), 3 could not be assigned to a specific road, and 4 were likely woodland caribou (*Rangifer tarandus caribou*) collisions on Fogo Island (as there are no moose). The remaining MVC locations were between 0.003m-250m off a road. We snapped these remaining points to the closest road, using the "snappoints" tool in the Geospatial Modelling Environment (Beyer, 2012). Our final MVC data set included 600 MVC locations across the island (Fig. 3-1). We did not include data on snow conditions for the analysis because the majority of MVCs occurred in the summer and fall (Fig. 3-2A-B).

3.3.2 MVC Hotspot Analysis

We used non-parametric kernel density estimation (KDE) to locate MVC "hotspots". KDE searches the input area for point collisions and then calculates the density of collisions within a specified search radius, or bandwidth, around the collision locations. Specifically, we used the "Kernel Density" tool within the Spatial Analyst toolbox in ArcMap with density classes grouped by natural breaks (Jenks). We wanted to visualize MVC hotspots at different spatial grains; therefore, we used bandwidths of 1km, 15km, and 50km to identify MVC hotspots at small, medium, and large grains respectively. Network density estimates, such as the ones performed by the SANET V4.1 extension to the ArcGIS framework (Okabe & Sugihara, 2012), may be more robust than areal densities but are only applicable at small spatial grains and therefore could not be run at our larger bandwidths (Fig. A2-1).

3.3.3 Spatial Correlates of MVCs

To determine the best predictors of MVC locations we follow methods of related studies (e.g., Danks & Porter, 2010; Hurley et al., 2007) by comparing environmental variables at known MVC locations (n=600) to environmental variables at random sites (n=3296) along the road network. Since moose are found throughout the entire island, the number of random points we used was determined by dividing the total length of all roads in Newfoundland (~17,710km) by the largest buffer search radius (see below for details on buffers) so that theoretically we could have at least one random point within the largest buffer (17,710.33/5.47km=3238 random points, rounded to 3300). We used ArcMaps's "Create Random Points" tool within the Data Management toolbox to generate 3300 random points along Newfoundland roads. We removed 4 of our random points because they fell outside the extent of the terrain ruggedness calculation (see below), resulting in a working set of 3296 random points.

We constructed buffers of three sizes around all of the MVC and random point locations to extract a series of potential explanatory variables for MVCs (see next section for descriptions of these variables). Buffer size was informed by the size of moose home ranges in Newfoundland and by the size of buffers used in previous work. Specifically, we used the "Buffer" tool within the Analysis toolbox in ArcMap to create three buffer sizes; a 5,471m radius (based on the mean home range size of 14 cow and 4 bull moose – see Table A2-3), a 2,736m radius (based on half of the mean home range size of 14 cow and 4 bull moose), and a 500m radius based on previous work (Danks & Porter, 2010; Hurley et al., 2007; Rea et al., 2014; Seiler, 2005; Snow et al., 2014). Finally, we clipped all MVC and random point buffers to the coastline of Newfoundland so that the buffers did not contain large amounts of ocean land cover.

3.3.4 Environmental Data

Based on previous studies (e.g., Danks & Porter, 2010; Dussault et al., 2006; Hothorn et al., 2012; Hurley et al., 2007; Joyce & Mahoney, 2001; Seiler, 2005), we identified 65 different discrete and continuous explanatory variables grouped into eight different classes of environmental data that may be useful predictors of MVC locations in Newfoundland. Based on previous studies, we identified specific hypotheses for the effect of each explanatory variable on the probability of MVC occurrence, however due to the large number of variables we combined the hypotheses into an overarching hypothesis for each of the eight model classes (Table 3-1). Below, we describe the eight classes of models (See Table 3-1 for a summary of classes of models and Table A2-4 for abbreviated variable definitions).

Composition Based Models We obtained the land cover of Newfoundland from the European Space Agency's GlobCover data (ESA GlobCover, 2009). These data were acquired from the MERIS sensor onboard the ENVISAT satellite mission, collected from January to December of 2009 at a resolution of 350m. We reclassified the original 14 land cover types present in Newfoundland into seven similar land cover types based on the original descriptions of the data (deciduous/ mixed forest, coniferous/ needleleaved deciduous forest, open water/ regularly flooded, developed, grassland, shrubland, and sparse vegetation/ bare areas). We extracted the proportion of each land cover type within all three buffers for each known MVC and random point using the "isectpolyrst" tool in the Geospatial Modelling Environment. The composition based models were split into three groups based on their buffer size: 500m, 2,736m, and 5,471m.

Terrain Based Models Elevation data were obtained from the Canadian Digital Elevation Model, with a scale of 1:250,000 and a resolution of 90m (GeoAccess Division, 2012). We calculated slope using the "Slope" tool within the Spatial Analyst toolbox in ArcMap. We determined terrain ruggedness using the "Vector Ruggedness Measure" tool, an add-on to ArcGIS, with 0 indicating no variation in the terrain and 1 indicating significant terrain variation (Sappington, Longshore, & Thompson, 2007). We extracted mean elevation, slope, and terrain ruggedness per buffer using the "isectpolyrst" tool within the Geospatial Modelling Environment. We calculated aspect using the "Aspect" tool within the Spatial Analyst toolbox in ArcMap and extracted aspect to each MVC location and random point using the "Extract Values to Points" tool in ArcMap.

Travel Corridor Based Models (Density) We obtained forest access road data from the Geoscience Atlas (Tamarack Geographic Technologies Ltd, 2013) and data for trails, transmission lines, and decommissioned railways from GeoGratis V2.0 (Natural Resources Canada, 2009) at a 1:250,000 scale at an island wide extent. We measured the length of each linear feature (i.e., forest access roads, trails, transmission lines, and railways) within each buffer with Geospatial Modelling Environment's "sumlinelengthsinpolys" tool. Then, we divided the length of each linear feature by its associated buffer size to calculate the density of each linear feature per buffer.

Travel Corridor Based Models (Distance) We used the same data sets for forest access roads, trails, transmission lines, and decommissioned railways as described above. We calculated the distance from each MVC or random point to the closest forest access road, trail, transmission line, and railway with the "Near" tool in the Analysis toolbox in ArcMap.

Disturbance or Road Based Models We used the Newfoundland road network from GeoGratis V2.0 (Canada Centre for Mapping and Earth Observation, 2013) to determine road classification (primary roads: highways, secondary roads: collectors or local streets) at each point of interest. We joined the road layer to the MVCs file and the random points file to specify the road classification for each MVC and random point. Due to the high level of disturbance caused by these variables, we obtained spatial data on operational mining areas in Newfoundland (found throughout the island, but ~60% are located on the Avalon Peninsula) at a scale of 1:250,000 (Natural Resources Canada, 2009), spatial data on developed areas (i.e., towns, cities, etc.) through the Newfoundland and Labrador Statistics Agency (2009), and 2011 population data from the 2011 Newfoundland and Labrador census (Statistics Canada, 2012). We used the population size of a developed area as a proxy for traffic volume (i.e., we expect more traffic near a town with a large population than a town with a small population). These population sizes for small, medium, and large towns were <10,000 individuals, between 10,000 to 100,000 individuals, and >100,000 individuals, respectively. We calculated the distance from each MVC or random point to the closest mining area, developed area (all sizes), large developed area, medium developed area, and small developed area with the "Near" tool in the Analysis toolbox in ArcMap. We determined road tortuosity using the "Calculate Sinuosity" tool, an add-on to ArcGIS (ArcGIS Team Python, 2011). Sinuosity ranges from 0 to 1 with a value of 1 indicating a straight line and values closer to 0 indicating more 'curvy' lines (ArcGIS Team Python, 2011). We joined the MVCs file and the random points file to the road tortuosity file to assign a road tortuosity value to each MVC and random point location.

Mitigation Based Models We obtained roadside vegetation cutting data from the Department of Transportation and Works for cutting projects issued by the Government of Newfoundland and Labrador from 2008 to 2013. We assigned the MVCs and random points that fell in a vegetation cutting zone a value of 1 and MVCs and random points that did not fall in a vegetation cutting zone a value of 0.

Water Feature Based Models We obtained datasets for the ocean, wetlands, rivers, and lakes at a scale of 1:250,000 (Natural Resources Canada, 2009). While we hypothesize that moose would be attracted to freshwater areas to drink, consume aquatic plants, and avoid insects (Peek, 1998) – increasing the likelihood of a MVC occurring closer to these features – we also hypothesize that moose would avoid saltwater areas – decreasing the likelihood of a MVC occurring closer to the ocean. We calculated the distance from each MVC or random point to the closest ocean, wetland, river, and lake with the "Near" tool within the Analysis toolbox in ArcMap.

Moose Density Based Models We obtained moose density data from the Newfoundland and Labrador Department of Environment and Conservation – Wildlife Division, who use a stratified-random block aerial survey design to calculate moose density data for each moose management area in the winter, as defined by Gosse, McLaren, and Eberhardt (2002). We joined the MVCs file and the random points file to the moose density file to assign a moose density value to each MVC and random point location.

3.3.5 Statistical Analysis

We built generalized linear models with a binomial error structure and a logit canonical link. The presence (1 = MVC) or availability (0 = random) of MVC locations was the dependent variable in our analyses. We constructed sets of generalized linear models within each of the eight classes of models using environmental data as described above (Table 3-1). We conducted both Pearson's and Spearman's correlation analyses among explanatory variables within each of the eight classes of models to avoid including highly correlated (rho>|0.5|) explanatory variables in the same model.

We used Akaike Information Criterion corrected for small sample size (AIC_c) to determine the most parsimonious models, within each of the eight classes, for explaining variation in the probability of MVC occurrence. We considered models with $\Delta AIC_c<2$ as potential parsimonious models (Burnham & Anderson, 2002). We retained the models within each of the eight classes that had a ΔAIC_c value of <2 and pooled all of these models into one combined class and ran the AIC_c analysis again to determine the overall top model out of all of the top models from each class (Fig. A2-2 for a flow diagram of the entire model selection analysis). In addition to the AIC_c values for each model we report delta AIC_c (ΔAIC_c), Akaike weights (ωAIC_c), log-likelihood (LL), and Nagelkerke's R^2 (R^2). After removing models containing pretending variables (sensu Anderson, 2008), our final model set consisted of a total of 297 models. We used the glm function and the AICcmodavg package (Mazerolle, 2015) in R v.3.1.2 for all of our analyses.

3.3.6 Model Validation

Many of the standard evaluation methods for logistic regression, such as receiver operating characteristic, are not appropriate methods since our data are presence/ available rather than presence/ absence (Boyce, Vernier, Nielsen, & Schmiegelow, 2002). K-fold cross validation can be used to evaluate prediction success with presence/ available data (Boyce et al., 2002). Using a k-fold partition of 10, we determined the adjusted cross-validation estimate of error for the top models within each of the eight classes (i.e., models with a $\Delta AIC_c<2$) using the cv.glm function within the boot package in R (Canty & Ripley, 2015). The R code and associated data for all analyses are available on figshare (Tanner, Leroux, & Saunders, 2015).

3.4 Results

3.4.1 MVC Hotspot Analysis

Based on our first objective, we identified many MVC hotspots at the 1km bandwidth (Fig. 3-3A) and fewer, but larger, hotspots at the 15km (Fig. 3-3B) and 50km (Fig. 3-3C) bandwidths using the kernel density tool within ArcMap. Small grain, 1km bandwidth size, MVC density ranged from 0.000 to 4.596 MVC/km^2. The small grain hotspot maps identified many localized hotspots for MVCs across the island of Newfoundland. Medium grain, 15km bandwidth size, MVC density ranged from 0.000 to 0.164 MVC/km^2. Medium grain hotspots were identified along primary roads, including the Trans-Canada Highway, on the Avalon Peninsula, and near towns such as Gander (population ~11,000), Grand-Falls Windsor (population ~13,700), and Corner Brook (population ~20,000). Large scale, 50km bandwidth size, MVC density ranged from 0.000 to 0.048 MVC/km^2. The main hotspot at this large scale is on the Avalon Peninsula, around the provincial capital and population center of St. John's. We also ran the hotspot analysis using ranges surrounding the selected bandwidths chosen (0.5-2km, 10-25km, and 40-75km) and found that the patterns demonstrated at our 1km, 15km, and 50km spatial grains were consistent across size classes.

3.4.2 Spatial Correlates of MVCs

We identified between one and four parsimonious models within each of the eight model classes we considered. Top models in all classes, except the disturbance or road based model class (Nag R^2=0.30) generally explained a small amount of variation in MVC occurrence (Nag R^2<0.10). Our top model within the *500m composition based* *models* buffer class had a ωAIC_c of 0.3603 and included the explanatory variables of proportion of: coniferous forest, water, developed areas, grassland areas, and shrubland areas within the 500m buffers (Table A2-5). Our top model within the *2736m composition based models* buffer class had a ωAIC_c of 0.5428 and included the explanatory variables of proportion of: coniferous forest, developed areas, grassland areas, and shrubland areas within the 2736m buffers (Table A2-6). Our top model within the *5471m composition based models* buffer class had a ωAIC_c of 0.2667 and included the explanatory variables of proportion of: coniferous forest, developed areas, grassland areas, shrubland areas, and bare areas within the 5471m buffers (Table A2-7). Our top model within the *terrain based models* class had a ωAIC_c of 0.3153 and included the explanatory variable of terrain ruggedness within the 500m buffers (Table A2-8). Our top model within the *travel corridor (density) based models* class had a ωAIC_c of 0.7897 and included the explanatory variables of density of: forest access roads, trails, transmission lines, and decommissioned railways within the 2736m buffers (Table A2-9). Our top model within the *travel corridor (distance) based models* class had a ωAIC_c of 0.5269 and included the explanatory variables of distance to trails, and transmission lines (Table A2-10). Our top model within the *disturbance or road based models* class had a ωAIC_c of 0.9934 and included the explanatory variables of road classification, road tortuosity, distance to mining areas, and distance to St. John's (used as a proxy for traffic volume) (Table A2-11). Our top model within the *mitigation based models* class had a ωAIC_c of 1 and included the explanatory variable of presence or absence of cut vegetation locations (Table A2-12). Our top model within the *water feature based models* class had a ωAIC_c of 0.9223 and included the explanatory variables of distance to: rivers, wetlands, ocean, and lakes (Table A2-13). Our top model within the *moose density based models* class had a ωAIC_c of 1 and included the explanatory variable of moose density (Table A2-14). For the model classes that used multiple scales, the spatial scale that ranked the highest in the final AIC_c analysis was the largest buffer size, 5,471m radius. However, it should be noted that even models at this spatial scale explained very little of the variance in the probability of MVCs (~2%).

3.4.2.1 Across Model Class Comparison

We combined the 19 top models (i.e., models with $\Delta AIC_c<2$, plus one null model) within each of the eight classes together to determine the top model out of all of the candidate models (Table A2-15, refer to Fig. A2-2 for a flow diagram of the entire model selection analysis). Based on our second objective, our top model across the eight model classes for determining what environmental features are associated with the locations of MVCs on the island was the disturbance or road based model, and had a ωAIC_c of 1 and a Nagelkerke R^2 value of 0.30. This model predicts a lower probability of occurrence of MVCs on secondary roads, tortuous roads, roads farther from mining areas, and roads farther from St. John's (Table 3-2).

3.4.3 Model Validation

The top 18 models across classes had model prediction error between 0.153 and 0.154 (Table A2-16 – does not include the null model). Our top model; a disturbance or road based model as described above, had an adjusted cross-validation estimate of error of 0.154 (Table A2-16). These validation results indicate that the majority of data points from the test groups were correctly identified as MVC or random point locations, as learned from the training groups.

3.5 Discussion

Wildlife-vehicle collisions are common and many studies have been conducted to determine what spatial or temporal factors influence the occurrence and location of WVCs (e.g., Danks & Porter, 2010; Hurley et al., 2007; Joyce & Mahoney, 2001; Rea et al., 2014). The population of Newfoundland, Canada is just under 500,000 people, but the moose densities are among the highest across the global distribution of this species. Even with a relatively small human population, there are approximately 600 MVCs per year, which poses a significant management challenge for provincial resource and transportation agencies. We took advantage of recent georeferenced MVC location data to map current hotspots for MVCs on the island of Newfoundland and developed models to determine the best spatial predictors of MVCs. Our study is unique because it addresses the issues of high MVC rates at a large spatial grain, and incorporates a very large collision dataset. There are local hotspots for MVCs across the island but at larger grains, not surprisingly, the Avalon Peninsula – an area where the majority of the population resides (57%) – had the highest density of MVCs. The best predictors of the probability of occurrence of MVCs are disturbance or road based variables; road classification, road tortuosity, distance to mining areas, and distance to St. John's (used as a proxy for traffic volume) which is in partial agreement with our hypothesis.

3.5.1 MVC Hotspot Analysis

Following our initial objective to identify and create maps of MVC hotspots, we identified hotspots at all three spatial grains (Fig. 3-3A-C). We expected MVC hotspots to be near areas with i) a high density of moose and/ or ii) a high density of vehicles. For example, Dussault et al. (2006) found an increase in MVCs with higher moose density and Danks and Porter (2010) showed that there was an increase in MVCs with an increase in traffic volume. Consistent with our expectation, the large scale MVC hotspot is on the Avalon Peninsula, an area that likely has the highest traffic volume on the island. This result is also consistent with other studies that have found traffic volume to be an important predictor of WVCs (Joyce & Mahoney, 2001; Rolandsen, Solberg, Herfindal, Van Moorter, & Saether, 2011). MVC hotspots along primary roads, specifically the Trans-Canada Highway, were identified at the medium spatial grain. Both the traffic volume, and traffic speed are generally higher on primary rather than secondary roads, and this could be a contributing factor to an increased likelihood of MVCs (Danks & Porter, 2010; Seiler, 2005). But, at the small spatial grain there appears to be localized MVC hotspots scattered across the island. This is not surprising because, while the majority of the population lives on the Avalon Peninsula near the capital of St. John's, the rest of the island's population is highly dispersed among the many bays and inlets – largely a legacy of the once flourishing cod fishing industry.

3.5.2 Spatial Correlates of MVCs

Overall, the top model for explaining the variance in the probability of MVC occurrence was a disturbance or road based model which included variables for road classification, road tortuosity, distance to mining areas, and distance to St. John's (used as a proxy for traffic volume). Support for this model is partially consistent with our initial hypothesis that traffic volume would affect MVC occurrence, as distance to St. John's was used as a proxy for traffic volume in lieu of actual traffic volume data and our model predicted a higher probability of MVC occurrence with decreasing distance to St. John's. The negative influence of secondary roads was expected since primary roads, such as highways, generally have higher traffic speeds than secondary roads, making it harder to avoid collisions (Danks & Porter, 2010; Hurley et al., 2007; Seiler, 2005). The road tortuosity variable ranges from 0 to 1, with 0 indicating more curved road sections and 1 indicating straight road sections. We found an increase in the probability of MVC occurrence on straight roads relative to curved roads (Huijser et al., 2008; MIWG, 2001), likely because drivers pay more attention along tortuous sections of road due to the increased risk of collisions associated with curves (Pynn & Pynn, 2004). Gunson, Chruszcz, and Clevenger (2005) proposed that a negative association of increased road tortuosity and ungulate-vehicle collision occurrence could occur because drivers may reduce the vehicle's speed when travelling around curves, decreasing the likelihood of a MVC. The increase in the probability of MVCs occurring closer to mining areas was unexpected, but it may be explained by the fact that mining areas usually operate on a 24 hour basis (Peetz & Murray, 2011), have constant traffic, and the roads connecting the mines to the highway may provide travelling corridors for moose, increasing the likelihood of a MVC occurring closer to a mining area.

Since our top model only explained ~30% of the variation in MVC occurrence, there is still a large amount of unexplained variation in the probability of MVC occurrence. In addition, the results obtained from the remaining model classes should be interpreted with caution since these models explained less than 10% of the variation in the probability of MVC occurrence. We included these model sets as they contained variables that were found to be good predictors of WVCs elsewhere. Consequently, our lack of support for these models is counter to our initial hypothesis and others, whose work indicated that variables such as distance to wetlands, and topographic variation have significant effects on the probability of MVC occurrence (e.g., Danks & Porter, 2010; Dussault et al., 2006; Hurley et al., 2007). While the overall model results may not explain a large portion of the variation in the probability of MVC occurrence, many of the predicted relationships are in agreement with results from other studies. For example, we found that there was a negative influence on the probability of occurrence of MVCs with increasing distance to wetlands, which is consistent with Danks and Porter's (2010) study conducted in western Maine, USA. We also found that increased terrain ruggedness had a strongly negative influence on the probability of MVC occurrence, which is similar to Hurley et al. (2007) who found that there were more MVCs on flat slopes in southeastern British Columbia, Canada.

While our study provides some evidence that we selected the right variables to explain MVCs, it must be acknowledged that we may not have used data of a fine enough resolution to detect strong relationships among our explanatory variables and MVC occurrence. For example, it may have been beneficial to have better resolution vegetation data, moose density data, and actual measurements of traffic volume. Alternatively, MVCs may be driven by factors not measured in our study, such as driver awareness, temporal variables, or weather. It must also be acknowledged that this study, although conducted on a large data set, only consists of one year of data. The top model explained ~30% of the variance in the probability of MVC occurrence, but this model must be tested on future MVC data to determine if it has high predictive strength. Although we found in Chapter 2 that browse and perhaps MVCs may be reduced in areas where roadside vegetation cutting has been performed, roadside vegetation cutting as a mitigation strategy did not come out as an important predictor of MVCs at large spatial grains. To improve on our work, additional spatial and temporal analyses could be conducted in Newfoundland using a georeferenced dataset encompassing a larger time span in order to refine the environmental features associated with MVCs and determine how static the hotspots are. Our study has identified hotspot areas of concern and the environmental variables that best predict the probability of MVCs. This research provides baseline information that managers may use to evaluate existing and design new MVC mitigation strategies. These strategies, however, must be designed within an adaptive management framework, as such a framework has provisions for monitoring the success of any strategy with the flexibility to modify management over time if a strategy is not effective.

3.6 Conclusion

Ungulate-vehicle collisions are often challenging to manage because ungulates are a popular game species that confers a benefit to local people and economies, but the costs of ungulate-vehicle collisions can be substantial (Storaas, Gundersen, Henriksen, & Andreassen, 2001; Timmermann & Rodgers, 2005; Wattles & DeStefano, 2011). This dichotomy could not be more evident than on the island of Newfoundland, where the public has split views on the issue of non-native moose on the island. Every year the government issues approximately 30,000 moose tags (Department of Environment and

Conservation, 2015a) and local outfitting for fishing and hunting is a $40 million industry (Department of Forest Resources and Agrifoods, 2003). But with ~600 MVCs per year, many residents would like to see significant reductions in the moose population on the island. Evidence of this concern was demonstrated in a recent class-action lawsuit that was filed against the Newfoundland and Labrador Government for alleged negligence for failing to manage the moose population in the province (Bailey, 2014; CBC News, 2011; Newfoundland and Labrador Supreme Court, 2011). Presently, the lawsuit has been dismissed by the Supreme Court of Newfoundland and Labrador and the provincial government was not found to be negligent, but the resulting appeal decision is still pending.

There are many different MVC mitigation strategies that could be implemented to reduce the number of MVCs. In the past, the Government of Newfoundland and Labrador had implemented several mitigation strategies including; public awareness campaigns, roadside vegetation cutting and herbicide application, increasing the number of moose hunting license and the length of the hunting season, roadside break-beam moose detection systems, and wildlife fencing (Policy, Planning, and Evaluation Division, 2014) (Fig. 3-4). The success of some of these mitigation strategies, however, has not been studied in detail. This year (2015), the province released a new five-year moose management plan, focusing on long-term moose population sustainability to allow hunting while mitigating against moose-human conflict (Wildlife Division, 2015). The plan focuses on increasing hunting quotas in moose management areas that boarder the

Trans-Canada Highway, and implementing two moose reduction zones to assist in removing roadside moose (Department of Environment and Conservation, 2015b).

Our top model predicts that the probability of a MVC is highest on primary roads, on straight sections of road, and in high traffic areas, with broad scale MVC hotspots around the Avalon Peninsula and TCH. A higher probability of collisions occur on primary roads rather than secondary roads, indicating that primary roads should receive mitigation strategies before secondary roads. Although we do not have data to speak to it, primary roads generally have higher speed limits than secondary roads; therefore a potential mitigation strategy could be to reduce vehicle speeds, focusing on specific MVC hotspots such as the Avalon Peninsula and TCH. Additionally, non-standard warning signs (e.g., indicating the number of collisions that have occurred this year or including flashing lights) could be implemented in MVC hotspots where roads are less tortuous and in the vicinity of mining areas. A more novel MVC mitigation strategy (currently in early production) would be to implement in-car detection systems, such as infrared thermal imaging (Huijser et al., 2008; Zhou, 2012). Other, more substantial strategies are highly effective at reducing MVCs (review by Huijser et al., 2009), such as wildlife fencing in combination with over or underpasses (Clevenger, Chruszcz, & Gunson, 2001), but significant research would have to be conducted to determine if they will be an effective and economical mitigation strategy that is also biologically reasonable on the island. For example, roadside fencing could act as a barrier to migratory species such as woodland caribou, which are both native to Newfoundland and threatened.

Perhaps the most important recommendation is that the provincial government of Newfoundland and Labrador continue to monitor the effectiveness of their existing MVC mitigation strategies and implement monitoring of any new strategies. This will allow mitigation strategies to be modified in a timely manner if they are deemed to be ineffective in their current state. Such a process requires setting clear management targets and a long-term commitment to evidence-based policy. We believe such an approach is essential to reaching a balance between the costs and benefits of moose and other species in Newfoundland, Canada and in any locations where wildlife-vehicle collisions are a concern.

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3.9 Figures

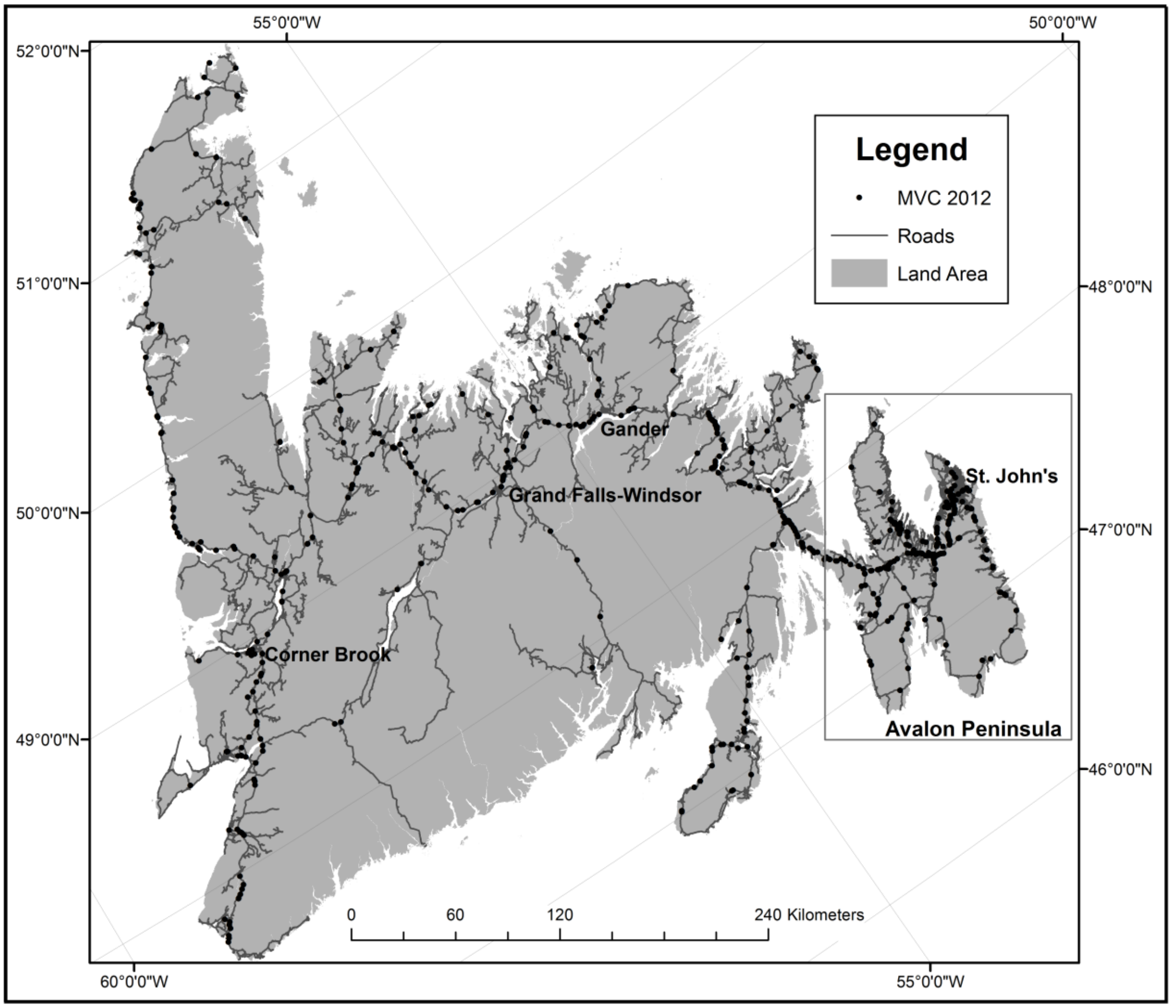

Figure 3-1: Map of the moose-vehicle collision (black points) locations from 2012 in Newfoundland, Canada. The grey linear features are roads. Four major cities are included and named, and the Avalon Peninsula is boxed to be used as reference points.

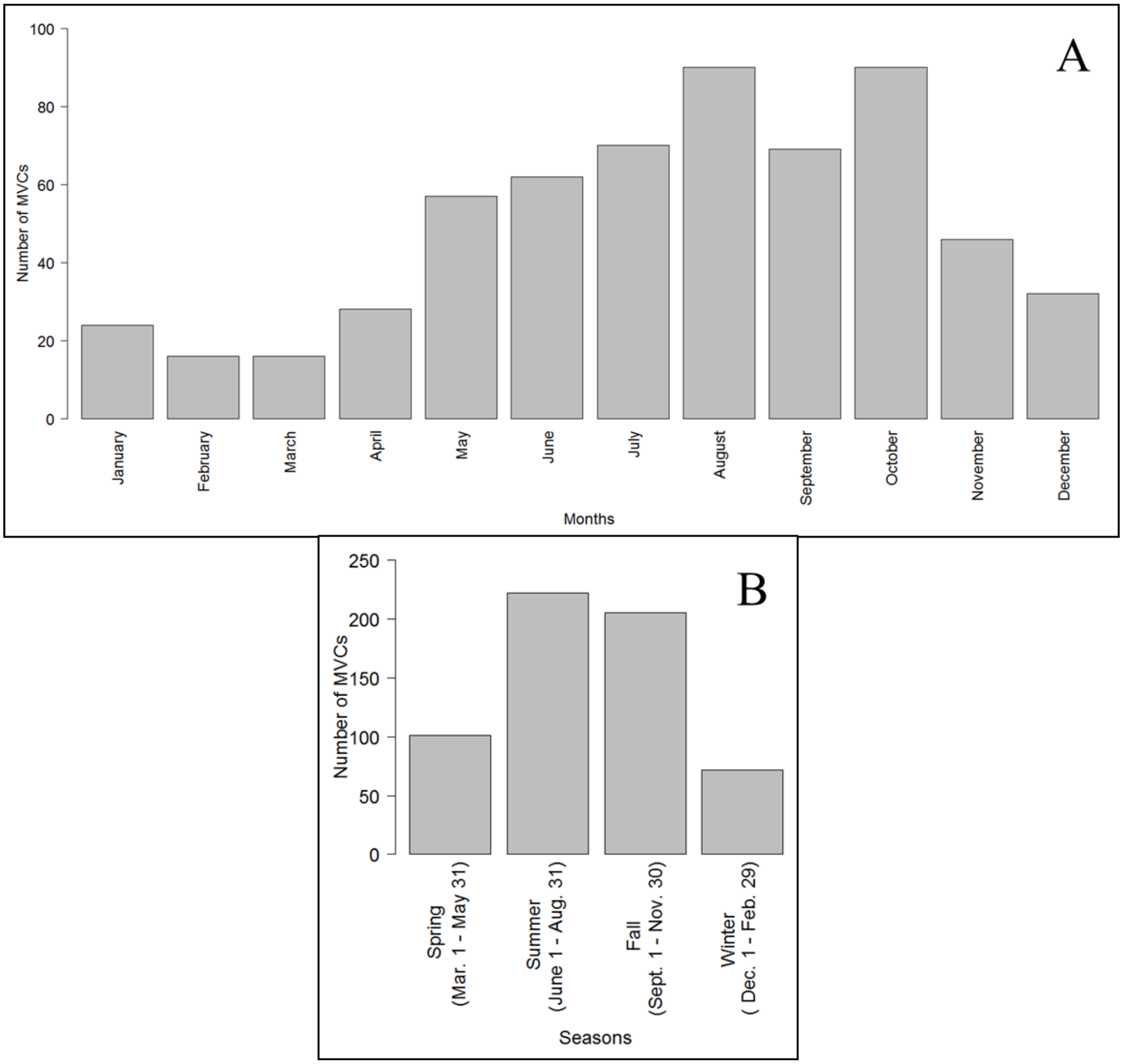

Figure 3-2A-B: Graph displaying the number of MVCs per month (A) and per season (B). Panel A displays the number of MVCs occurring each month in 2012 (January – Decmeber). Panel B displays the number of MVCs occurring each season: Spring: March 1 – May 31, Summer: June 1 – August 31, Fall: September 1 – November 30, and Winter: December 1 – February 29.

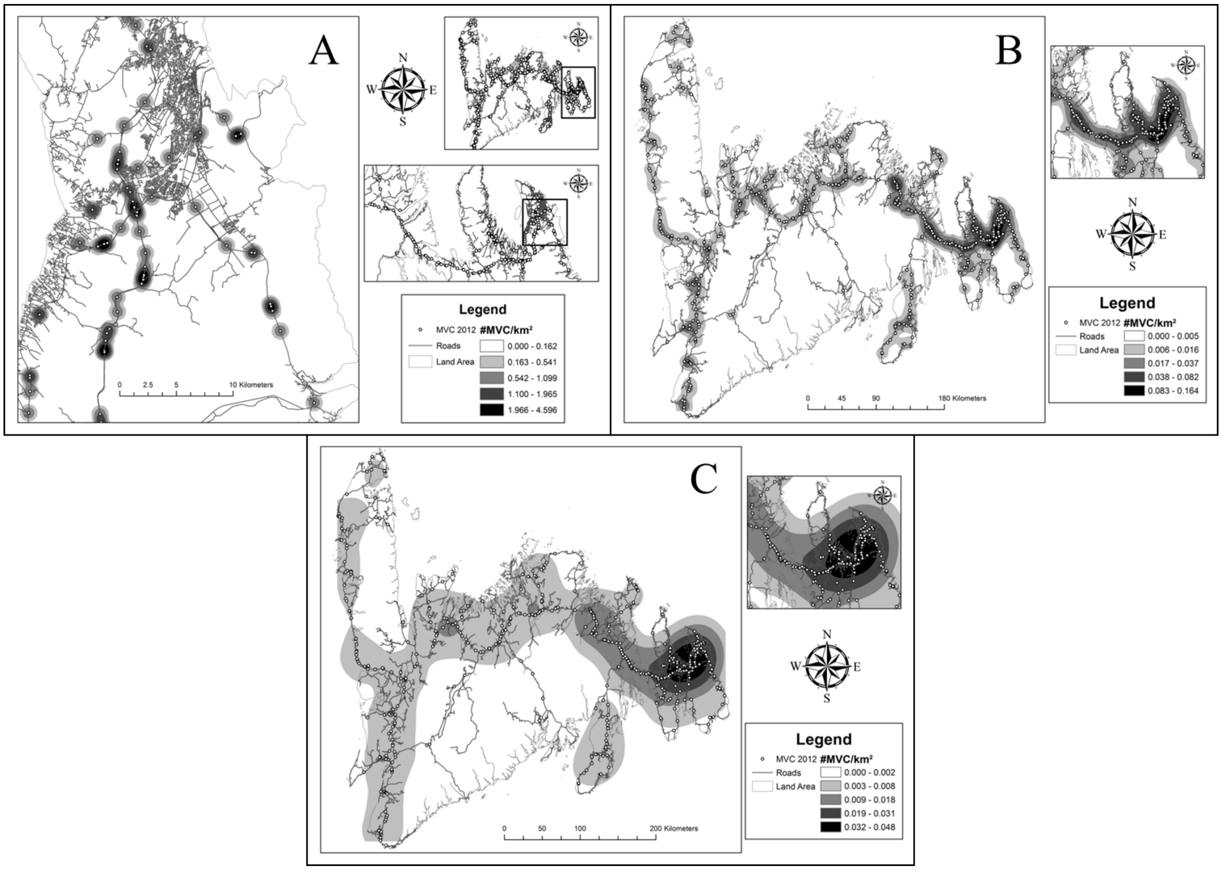

Figure 3-3A-C: Map displaying the hotspots located using kernel density estimation at a 1km (panel A), 15km (panel B), and 50km (panel C) bandwidth with the "Kernel Density" tool within the Spatial Analyst toolbox in ArcMap. Panel A displays hotspots at the small spatial grain throughout the island. Panel B displays hotspots occurring more frequently along the Trans-Canada Highway rather than on secondary roads. Panel C displays hotspots occurring more frequently on the Avalon Peninsula on the eastern side of the island rather than throughout central and western Newfoundland. The darker the grey, the higher the density of moose-vehicle collisions/km^2. The grey outlined circles designate MVC location for 2012 and the linear light grey features indicate the road network of Newfoundland.

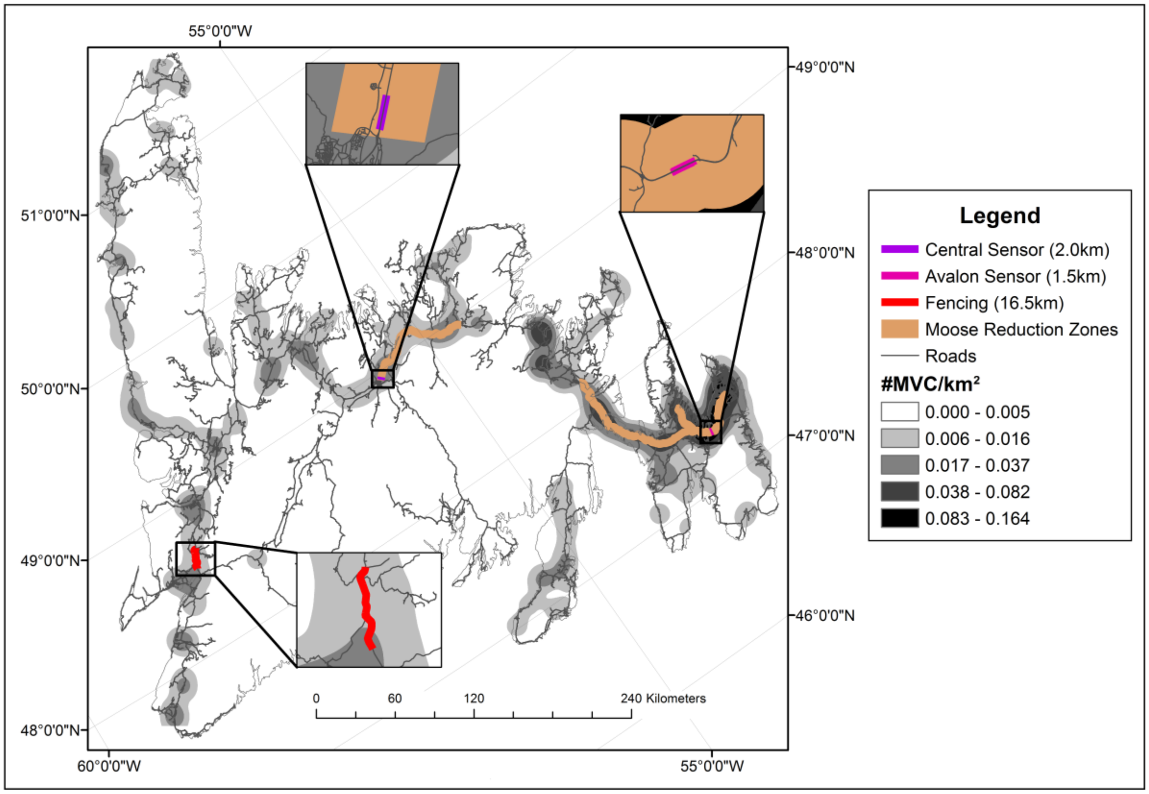

Figure 3-4: Map of the location of some of the mitigation strategies implemented in Newfoundland, Canada. The grey linear features represent roads, the purple linear feature represents a 2.0km section of highway sensors, the pink linear feature represents a 1.5km section of highway sensors, and the red linear feature represents a 16.5km section of highway fencing. The orange areas represent two moose reduction zones, and the white to black surface areas represents the density of moose determined through the 15km bandwidth kernel density estimation. The zoomed in boxes are not the same scale as the overall map, but the lengths of the relevant features are provided in the legend.

3.10 Tables

Table 3-1: Summary of the eight classes of models, associated hypothesis, and potential explanatory variables within each of the classes of generalized linear models. Included in each model class is an intercept only model as the null model to ascertain if adding additional fixed effects improves the AIC_c.

Classes of Models	Number of Models in Class	Hypothesis	Potential Explanatory Variables
Small Buffer Composition Based Models	500m Buffer: 72	The probability of a MVC is affected by the suitability of the surrounding habitat for nutritional resources and cover, defined by the proportion of land cover types (Nielsen, Anderson, & Grund, 2003; Peek, 1998; Seiler, 2005).	1. Proportion of deciduous-mixed forest (3 buffer sizes) 2. Proportion of coniferous-needleleaved deciduous forest (3 buffer sizes) 3. Proportion of open water/ regularly flooded areas (3 buffer sizes) 4. Proportion of developed areas (3 buffer sizes) 5. Proportion of grassland (3 buffer sizes) 6. Proportion of shrubland (3 buffer sizes) 7. Proportion of sparse vegetation/ bare areas (3 buffer sizes)
Medium Buffer Composition Based Models	2736m Buffer: 36		
Large Buffer Composition Based Models	5471m Buffer: 49		
Terrain Based Models	14	The probability of a MVC is affected by the topographic features of an area that can attract moose due to increased solar radiation and therefore vegetation, preclude access due to impassable features, or guide moose into road areas (Dussault et al., 2006; Hurley et al., 2007).	1. Terrain Ruggedness (3 buffer sizes) 2. Aspect 3. Slope (3 buffer sizes)
Travel Corridor Based Models (Density)	36	The probability of a MVC is affected by the density of a travel corridor within a buffered area because moose may use the travel corridor to move because it is easier than walking through forest, and the travel corridor may lead the moose onto a busier road (Finder, Roseberry, & Woolf, 1999; Seiler, 2005).	1. Density of Forest Access Roads (3 buffer sizes) 2. Density of Transmission Lines (3 buffer sizes) 3. Density of Decommissioned Railways (3 buffer sizes) 4. Density of Trails (3 buffer sizes)

Travel Corridor Based Models (Distance)	10	The probability of a MVC is affected by the distance to a travel corridor because moose may use the travel corridor to move because it is easier than walking through forest, and the travel corridor may lead the moose onto a busier road (Christie & Nason, 2004; Finder et al., 1999; Seiler, 2005).	1. Distance to Forest Access Roads 2. Distance to Transmission Lines 3. Distance to Decommissioned Railways 4. Distance to Trails
Disturbance or Road Based Models	60	The probability of a MVC is affected by the amount of disturbance because moose behaviour is influenced by the amount of traffic and associated disturbance of an area (Danks & Porter, 2010; Eldegard, Lyngved, & Hjeljord, 2012; Huijser et al., 2008; Malo et al., 2004; MIWG, 2001; Rolandsen et al., 2011; Seiler, 2005).	1. Distance to Developed Areas (All, Large, Medium, Small) 2. Distance to Mining Areas 3. Road Classification 4. Road Tortuosity
Mitigation Based Models	2	The probability of a MVC is affected by the presence or absence of a mitigation strategy because mitigation strategies are designed to reduce the number of MVCs occurring (Clevenger et al., 2001; McCollister & van Manen, 2010; Rea, 2003; T. L. Sullivan, Williams, Messmer, Hellinga, & Kyrychenko, 2004; Tanner & Leroux, 2015).	1. Presence or Absence of Roadside Vegetation Cutting Location
Water Feature Based Models	16	The probability of a MVC is affected by the distance to freshwater water features because moose would be attracted to avoid insects, drink, and feed on aquatic plants and would avoid saltwater water features (Peek, 1998).	1. Distance to Oceans 2. Distance to Wetlands 3. Distance to Rivers 4. Distance to Lakes
Moose Density Based Models	2	The probability of a MVC is affected by the density of moose in an area (Dussault et al., 2006; Joyce & Mahoney, 2001; Rolandsen et al., 2011).	1. Moose Density in each Moose Management Area

Table 3-2: Generalized linear model analysis results for the top model out of all of the top models for explaining the variation in the probability of occurrence of MVCs.

Model → Disturbance or Road Based : Probability of MVC ~ –3.13 – 2.65 * Road Classification (Secondary Roads) + 3.15 * Sinuosity – 0.000005 * Distance to Mining Areas – 0.000001 * Distance to Developed Areas (Large)		
Variable	**Estimate**	**Standard Error**
Intercept (control)	-3.13	0.83
Road Classification - Secondary Roads	-2.65	0.14
Sinuosity	3.15	0.85
Distance to Mining Areas	< -0.01	< 0.01
Distance to Developed Areas (Large)	< -0.01	0.00

CHAPTER 4

Thesis Synopsis

In addition to a large moose population, there are over 17,000km of roads, including the Trans-Canada Highway, that bisect a significant portion of moose habitat on the island of Newfoundland. Therefore, it is not surprising that Newfoundland has one of the highest moose-vehicle collision (MVC) rates across the range of moose. From 2000 to 2010 there were approximately 4,400 MVCs, with 18 human fatalities and 900 injuries reported on the island of Newfoundland (Policy, Planning, and Evaluation Division, 2014). In order to reduce the number of collisions, mitigation strategies such as roadside fencing, moose population control, or highway speed limit reduction are often implemented (see review in Huijser et al., 2008). The success of any mitigation strategy, however, is context dependent; therefore, all strategies need to be monitored so that they can be modified if they are not successful. The goals of this thesis were to i) investigate the effectiveness of roadside vegetation cutting as a mitigation strategy for MVCs, ii) identify hotspots for MVCs at different spatial grains, and iii) determine the key environmental predictors of MVCs on the island of Newfoundland.

In chapter 2 I assessed if a common MVC mitigation strategy, roadside vegetation cutting, acted as an attractant for moose to browse in roadside areas with cut vegetation. To do so, I designed a field study to compare the proportion of moose browse in roadside areas within six paired sites of recently cut (2008-2013) and uncut vegetation (not cut since at least 2008) in central and eastern Newfoundland. Counter to my initial hypothesis and previous work by Child, Barry, and Aitken (1991) and Rea (2003), I found evidence for lower amounts of moose browse in recently cut roadside areas than uncut areas. Specifically, the proportion of browsed plants in the uncut control areas was on average 1.5 to 23.2 times higher than the proportion of plants browsed in the 2008-2010 and 2011-2013 cut treatment areas, respectively. These results provide evidence that moose may not be attracted to recently cut roadside areas solely to browse vegetation regrowth. Roadside vegetation cutting is usually implemented to improve driver visibility but my results suggest that it may also reduce the occurrence of moose browsing along roadsides, which may lead to fewer MVCs in areas where roadside vegetation has been recently cut. However, moose may be attracted to roadsides for other reasons, such as using roads as travel corridors, especially in winter (Del Frate & Spraker, 1991; Schwartz & Bartley, 1991). In this chapter, I also developed a technique, using segmented regression, to determine preferred plants browsed by moose by identifying a threshold in browse frequency, a technique which could significantly reduce browse sampling time in the field.

In chapter 3 I conducted a spatial analysis of MVC hotspots and spatial correlates of MVCs on the island of Newfoundland. In the first part of this chapter, I used kernel density estimation to identify MVC hotspots on the island at small (1km), medium (15km), and large (50km) spatial grains. I identified many small scale hotspots throughout the island, medium scale hotspots across the Trans-Canada Highway, and a large scale hotspot on the Avalon Peninsula. These hotspots are logical areas for initial implementation of mitigation strategies on the island. Next, I took advantage of recently collected and precise MVC location data across the island to conduct a spatial analysis using ArcGIS 10.2, Geospatial Modelling Environment, and model selection to identify the key environmental variables for predicting the probability of MVC occurrence on the island. Specifically, the most parsimonious model predicts a higher probability of MVC occurrence on primary roads, along straight road sections, close to mining areas, and close to St. John's. As with the hotspot analysis, the results of this analysis will aid management officials in determining where to implement mitigation strategies across the island.

4.1 Limitations of the Studies and Future Work

There are frequently unavoidable issues when conducting field studies. For my study, control areas for the empirical assessment of roadside vegetation clearing were not true controls but rather areas that had not been cut since at least 2008. The inference of the study would have been stronger if I could have used true controls or a larger range of sites with varying ages of vegetation cutting (e.g., cut in 1995, 2000, 2005, 2010), but these data were unavailable. Also, it was difficult to find sites that were not recently cut, so the sample size is relatively small (i.e., six paired treatment and control areas). However, given the large effect sizes I report, I am confident that the conclusions are robust. Future research on roadside vegetation cutting should involve working with the provincial government to define control areas where roadside vegetation cutting will no longer be conducted (warning signs could be implemented in these areas to inform drivers about the uncut vegetation) and by sampling more sites overall. This work could be conducted over a longer time span to determine the temporal scale for roadside vegetation cutting that is the most effective at reducing moose foraging while maximizing the time between cutting events to be the most cost-effective. Additionally, cameras could be deployed in roadside areas to see what moose do when they enter roadside areas (i.e., if they browse, cross the road, use the roadside as a travel corridor etc.) as my study did not measure if more moose browsing in roadside areas actually leads to a higher risk of MVCs.

Like field studies, large-scale spatial studies are also limited by data. In my case, finer resolution land cover and moose density data would be beneficial as they may allow a more accurate representation of factors affecting the probability of occurrence of MVCs on the island. Furthermore, actual measures of traffic volume (e.g., using traffic counters) and traffic speeds (e.g., using speed trap cameras) would allow researchers to determine if there are traffic volume or speed thresholds in MVC occurrence. For example, perhaps MVCs are more likely to occur on a road that has an average annual daily traffic volume of over 15,000 vehicles and perhaps MVCs are also more likely to occur on roads that have a speed limit of 100km/h. These detailed data would allow for the implementation of more directed mitigation strategies, such as enforced reduced speed limits, to decrease the number of MVCs

My modelling exercise clearly identified disturbance or road based variables as the most parsimonious explanation for the probability of occurrence of MVCs. This model, however, should be tested on future MVC data to determine if it has high predictive value. If the top model does not predict independent MVC data on the island very well, it should be modified accordingly.

Future studies could work on implementing traffic counters and speed trap cameras to help enforce speed limits and could also endeavour to conduct this research over a longer time span to refine the environmental variables of importance and determine if MVC hotspots are dynamic over time. The variability in MVC hotspot locations over time will help inform management strategies. For example, if the MVC hotspots are highly variable throughout time, then a permanent mitigation strategy such as fencing may not be as effective or cost efficient as temporary wildlife warning signs which can be moved to new areas when necessary.

4.2 Significant Contributions of this Thesis

This thesis is a novel exploration of the issue of high occurrence of MVCs with case studies on the island of Newfoundland, specifically dealing with i) determining the effectiveness of roadside vegetation cutting as a mitigation strategy, ii) identifying MVC hotspots, and iii) determining the environmental variables that have the highest influence on the occurrence of MVCs. While my thesis deals with MVCs in Newfoundland specifically, the methods and results of this work could be applied to any region attempting to manage ungulate-vehicle collisions. My key contributions to the field of wildlife and conservation biology are:

- The first empirical data with evidence that, counter to prevailing knowledge, roadside areas with recently cut vegetation may not, in fact, be more attractive areas for moose to browse than roadside areas with uncut vegetation.

- Developing a surrogate technique to rapidly identify preferred forage species for moose, which could significantly reduce time in the field when conducting vegetation sampling.
- A kernel density estimation analysis of MVC hotspots at small (1km), medium (15km), and large (50km) spatial grains across the island of Newfoundland, which can be used to determine areas to implement MVC mitigations strategies.
- A robust statistical analysis of a large wildlife-vehicle collision spatial data set, which identified disturbance or road based variables as the best predictors of the probability of MVC occurrence in Newfoundland. This analysis corroborates other studies that have found variables such as road tortuosity and distance to urban centers as being good predictors of wildlife-vehicle collisions.

4.3 Overall Management Implications

The high numbers of MVCs on the island of Newfoundland will not be significantly reduced unless effective mitigation strategies are implemented. Based on the results of the empirical research conducted for this thesis, I recommend the following for MVC managers on the island of Newfoundland:

- Continue frequent roadside vegetation cutting to decrease the attractiveness of the roadside area for moose to browse (from my data, one to seven year old cuts are less attractive to moose than cuts greater than seven years old)
- Implement mitigation strategies on straight, primary roads (such as the Trans-Canada Highway), near mining areas, and St. John's

- Implement mitigation strategies first on the Avalon Peninsula before expanding to the remainder of Newfoundland
- Implement mitigation strategies first on primary roads on the Avalon Peninsula
- Monitor all implemented mitigation strategies to determine their level of effectiveness, allowing for modifications to be made if necessary

4.4 References

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Appendix 1 (A1): Chapter 2 Additional Sampling Information, Data, and Results

In this appendix we present additional information on sampling sites, variables, correlations, and models for the effect of roadside vegetation cutting on moose browsing.

Table A1-1: Site description including; GPS locations, road speed limit, width, elevation, presence of water bodies, moose density and the gradient for both the road and tree sides of the site for the cut treatment (TRT) and uncut control (CRL) sites collected from June 17th – July 23rd 2014 in Newfoundland, Canada. For the locations; BAD: Badger, GFW: Grand Falls-Windsor, GAN: Gander Bay, MAN: La Manche Provincial Park, REN: Renews-Cappahayden, and SPA: Spaniards Bay.

	BAD TRT	**BAD CRL**	**GFW TRT**	**GFW CRL**	**GAN TRT**	**GAN CRL**	**REN TRT**	**REN CRL**	**MAN TRT**	**MAN CRL**	**SPA TRT**	**SPA CRL**
Latitude	48.945035	48.816628	49.008013	49.052005	49.348650	49.313023	46.851091	47.143087	47.203047	47.344274	47.605001	47.600894
Longitude	−56.095413	−56.582799	−55.577648	−55.592012	−54.381017	−54.433646	−52.973544	−52.901577	−52.902267	−52.915037	−53.348765	−53.342005
Year cut	2009	pre-2008	2009	pre-2008	2011	pre-2008	2010	pre-2008	2013	pre-2008	2011	pre-2008
Road speed	80km/h	80km/h	50km/h	60km/h	80km/h	80km/h	80km/h	80km/h	80km/h	80km/h	80km/h	50km/h
Site width	13.7m	13.7m	16.0m	16.0m	14.1m	14.1m	15.5m	15.5m	14.5m	14.5m	11.2m	11.2m
Elevation	120m	201m	95m	98m	40m	11m	43m	80m	66m	155m	105m	94m
Water body	No	Yes	Yes	No	Yes	No	Yes	No	Yes	No	No	No
Gradient road	0.50	0.60	0.54	0.55	0.70	0.55	0.50	0.58	0.59	0.21	0.57	0.44
Gradient tree	0.42	0.27	No Slope	No Slope	No Slope	No Slope	No Slope	0.67	No Slope	0.46	0.45	0.46
Traffic region	Off Avalon	Off Avalon	Off Avalon	Off Avalon	Off Avalon	Off Avalon	On Avalon	On Avalon	On Avalon	On Avalon	On Avalon	On Avalon
Moose density (moose/km^2)	1.05 moose/km^2	1.05 moose/km^2	1.95 moose/km^2	1.95 moose/km^2	1.10 moose/km^2	1.10 moose/km^2	3.63 moose/km^2	3.63 moose/km^2	3.63 moose/km^2	3.63 moose/km^2	1.58 moose/km^2	1.58 moose/km^2

Table A1-2: Pictures of one of our control, treatment 1, and treatment 2 sampling sites, showing the height of the vegetation and the width of the cut (in the treatment areas). A black arrow indicates the location of a person (height 5’6” or 1.68m) as a reference for the height of the vegetation.

	Site 8: Control – not cut since at least 2007 Location: Grand Falls-Windsor Cut width: matched to paired treatment (16m)
	Site 8: Treatment 1 – cut between 2008-2010 Location: Grand Falls-Windsor Cut width: 16m
	Site 17: Treatment 2 – cut between 2011-2013 Location: Gander Cut width: 14.1m

Table A1-3: Potential hypotheses for the effect that each explanatory variable would have individually on the proportion of moose browse in roadside areas in Newfoundland, Canada.

Explanatory Variable	**Discrete or Continuous Variable**	**Effect on Proportion of Moose Browse**
Treatment type	Discrete	The more recently the vegetation was cut, the greater the proportion of moose browse due to moose preferentially feeding on plant regrowth.
Water bodies	Discrete	Presence of water bodies would increase the proportion of moose browse due to moose being attracted to the water bodies to drink, feed on aquatic plants, and avoid insects (Peek 1998).
Traffic region	Discrete	The Avalon Peninsula has higher traffic volumes and therefore more disturbance than central Newfoundland, resulting in avoidance of the roadside area by moose and a decrease in the proportion of browse.
Width of site	Continuous	The larger the width, the greater the proportion of moose browse due to the moose not having to venture as close to the road to feed.
Road speed limit	Continuous	The faster the speed limit, the greater the disturbance the traffic causes, resulting in a decrease in the proportion of moose browse.
Gradient up to the roadside	Continuous	The steeper the roadside gradient the greater the challenge for moose to maneuver out of the roadside area, resulting in the moose remaining in the roadside area and increasing the proportion of browse.
Gradient up to the tree-side	Continuous	The steeper the tree-side gradient, the greater the challenge for moose to maneuver into the roadside area, resulting in moose not entering into the

		roadside area, causing a decrease in the proportion of browse.
Moose density	Continuous	Higher moose density would increase the proportion of moose browse in roadside areas because a larger number of moose would live and forage in the area.
Plant preference index	Continuous	A higher proportion of preferred or high quality plants would increase in the proportion of moose browse in roadside areas due to the moose being attracted to the area to feed on preferred or high quality species.

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Peek, J. M. (1998). Habitat Relationships. In A. W. Franzmann & C. C. Schwartz (Eds.), *Ecology and Management of the North American Moose* (1st ed., pp. 351-375). Washington, D.C., USA: Smithsonian Institution Press.

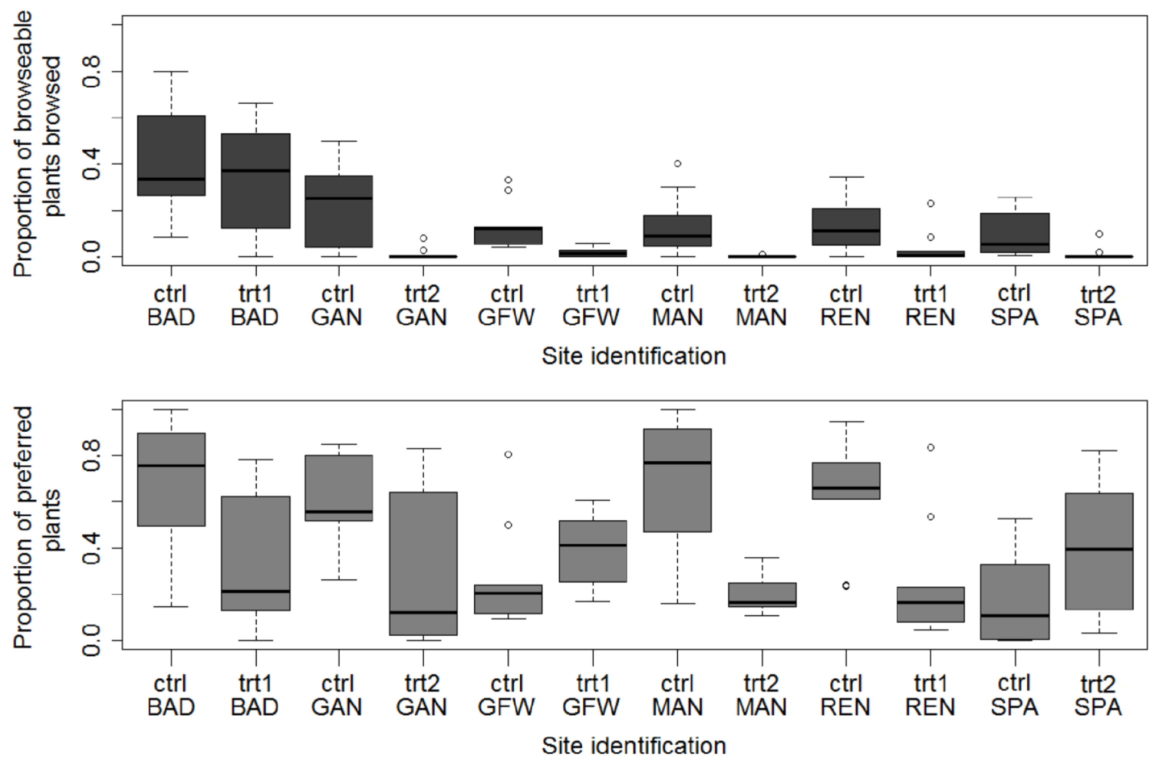

Figure A1-4: The proportion of moose browsed plants (dark grey) and the proportion of preferred plants (light grey) for each treatment (trt1 & trt2) and control (ctrl) site. Preferred plants are the 14 forage species that had significantly higher browse frequency as identified with our segmented regression analysis (see text for details). The locations; BAD: Badger, GFW: Grand Falls-Windsor, GAN: Gander Bay, MAN: La Manche Provincial Park, REN: Renews-Cappahayden, and SPA: Spaniards Bay. Treatment 1: BAD, GFW, REN, and Treatment 2: GAN, MAN, SPA.

Table A1-5: Pearson's and Spearman's correlation analyses were performed to determine which explanatory variables to include as fixed effects in the models. Pearson's correlation was performed when both variables were continuous and Spearman's correlation was performed when either one or both variables were discrete. The tolerance for Type 1 error was set at $\alpha=0.05$, therefore variables were considered correlated if the p-value was <0.05.

Explanatory Variables	**Spearman`s**		
	rho	**S**	**p-value**
Treatment Year Group & Water Bodies	0.48	109566.4	1.67e-07
Treatment Year Group & Width of Cut	-0.12	234078.7	0.24
Treatment Year Group & Road Speed	0.25	158036.9	0.01
Treatment Year Group & Road-side Gradient	0.52	100039.6	6.14e-09
Treatment Year Group & Tree-side Gradient	-0.41	296638.8	8.91e-06
Treatment Year Group & Traffic Region	0.08	193440.0	0.42
Treatment Year Group & Moose Density	0.00	209934.0	1.00
Treatment Year Group & Site Quality	-0.30	272145.8	0.00
Water Bodies & Width of Cut	0.25	157988.8	0.01
Water Bodies & Road Speed	0.06	196400.4	0.51
Water Bodies & Road-side Gradient	0.17	173955.8	0.08
Water Bodies & Tree-side Gradient	-0.55	325148.4	7.78e-10
Water Bodies & Traffic Region	-0.17	245419.3	0.08
Water Bodies & Moose Density	0.05	199393.3	0.61
Water Bodies & Site Quality	-0.13	236873.4	0.19
Width of Cut & Traffic Region	-0.10	230421.5	0.32
Road Speed & Traffic Region	0.16	176573.3	0.10
Road-side Gradient & Traffic Region	0.05	199798.3	0.62
Tree-side Gradient & Traffic Region	0.52	101740.7	1.15e-08
Traffic Region & Moose Density	0.69	64428.06	< 2.20e-16
Traffic Region & Site Quality	-0.09	228453.0	0.36
Explanatory Variables	**Pearson`s**		
	cor	**t**	**p-value**
Width of Cut & Road Speed	-0.01	-0.13	0.90
Width of Cut & Road-side Gradient	0.12	1.26	0.21
Width of Cut & Tree-side Gradient	-0.43	-4.87	3.93e-06
Width of Cut & Moose Density	0.44	4.99	2.42e-06
Width of Cut & Site Quality	0.07	0.75	0.45
Road Speed & Road-side Gradient	-0.05	-0.46	0.64
Road Speed & Tree-side Gradient	0.08	0.87	0.38

Road Speed & Moose Density	0.18	1.89	0.06
Road Speed & Site Quality	0.24	2.53	0.01
Road-side Gradient & Tree-side Gradient	-0.38	-4.24	4.76e-05
Road-side Gradient & Moose Density	-0.07	-0.74	0.46
Road-side Gradient & Site Quality	-0.29	-3.11	0.00
Tree-side Gradient & Moose Density	0.21	2.21	0.03
Tree-side Gradient & Site Quality	0.26	2.72	0.01
Moose Density & Site Quality	-0.01	-0.07	0.94

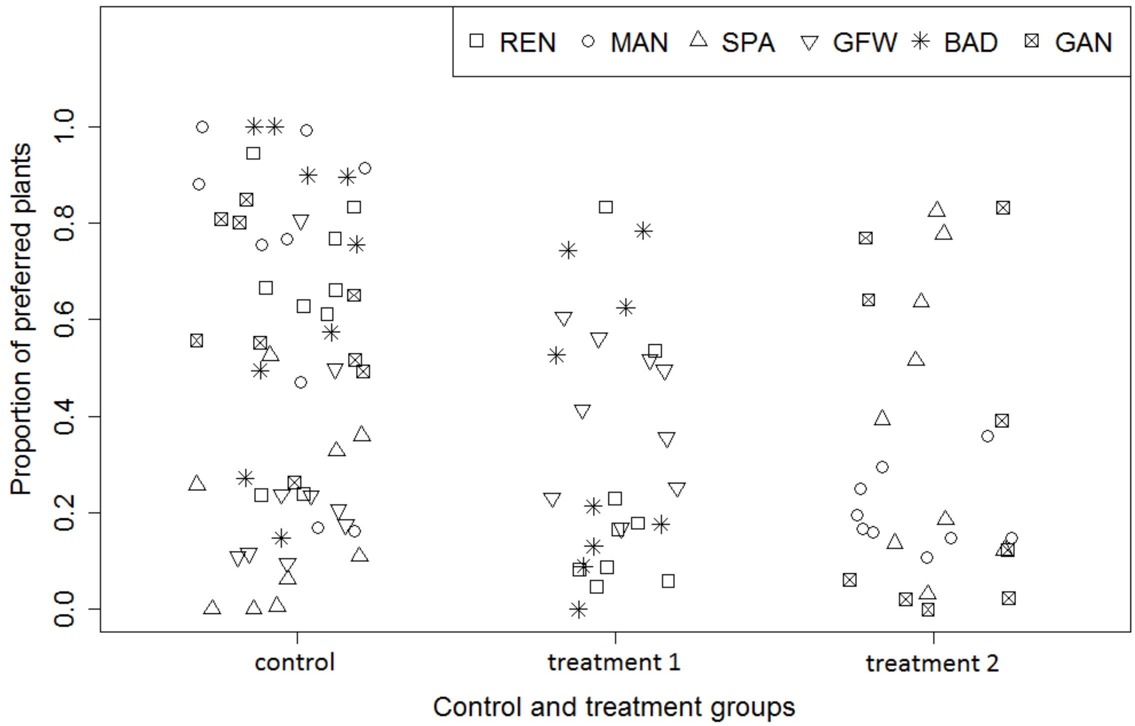

Figure A1-6: Displaying the correlation between the proportion of preferred plants per plot and the three treatment types. There were more preferred plants present in the control areas than in the treatment areas (*rho*=−0.30, S=272145.8, *P*=0.002). Since we were testing for the effect that roadside vegetation cutting had on the proportion of moose browse in roadside areas (and through further AIC_c analysis), treatment type was used as the main explanatory variable rather than preferred plants. For the control and treatment groups: control sites: not cut since at least 2008, treatment 1 sites: cut from 2008-2010, and treatment 2 sites: cut from 2011-2013. For the locations; BAD: Badger, GFW: Grand Falls-Windsor, GAN: Gander Bay, MAN: La Manche Provincial Park, REN: Renews-Cappahayden, and SPA: Spaniards Bay. Treatment 1: BAD, GFW, REN, and Treatment 2: GAN, MAN, SPA.

Table A1-7: Two generalized linear mixed-effects models used to determine if treatment type or preferred plants was a better predictor of the proportion of browsed plants. The variables plot number nested within site id were included as random effects in all models.

Model[a]	Description	k[b]	LL[b]	AIC_c[b]	ΔAIC_c[b]	ωAIC_c[b]	Marginal R^{2b}	Conditional R^{2b}
1	treatment type	5	-338.32	686.65	0.00	1.00	0.34	0.42
2	proportion of preferred plants 14spp	4	−361.30	730.61	43.96	0.00	0.11	0.24

[a] Models are ranked with Akaike Information Criterion, corrected for small sample size (AIC_c)

[b] Key: k, number of parameters; LL, log-likelihood; AIC_c, Akaike Information Criterion, corrected for small sample size; ΔAIC_c, the difference in the AIC_c; ωAIC_c, models weights; Marginal R^2, Nakagawa and Schielzeth's Marginal R^2 which is the proportion of variance explained by the fixed factors alone; Conditional R^2, Nakagawa and Schielzeth's Conditional R^2 which is the proportion of variance explained by both the fixed and random factors.

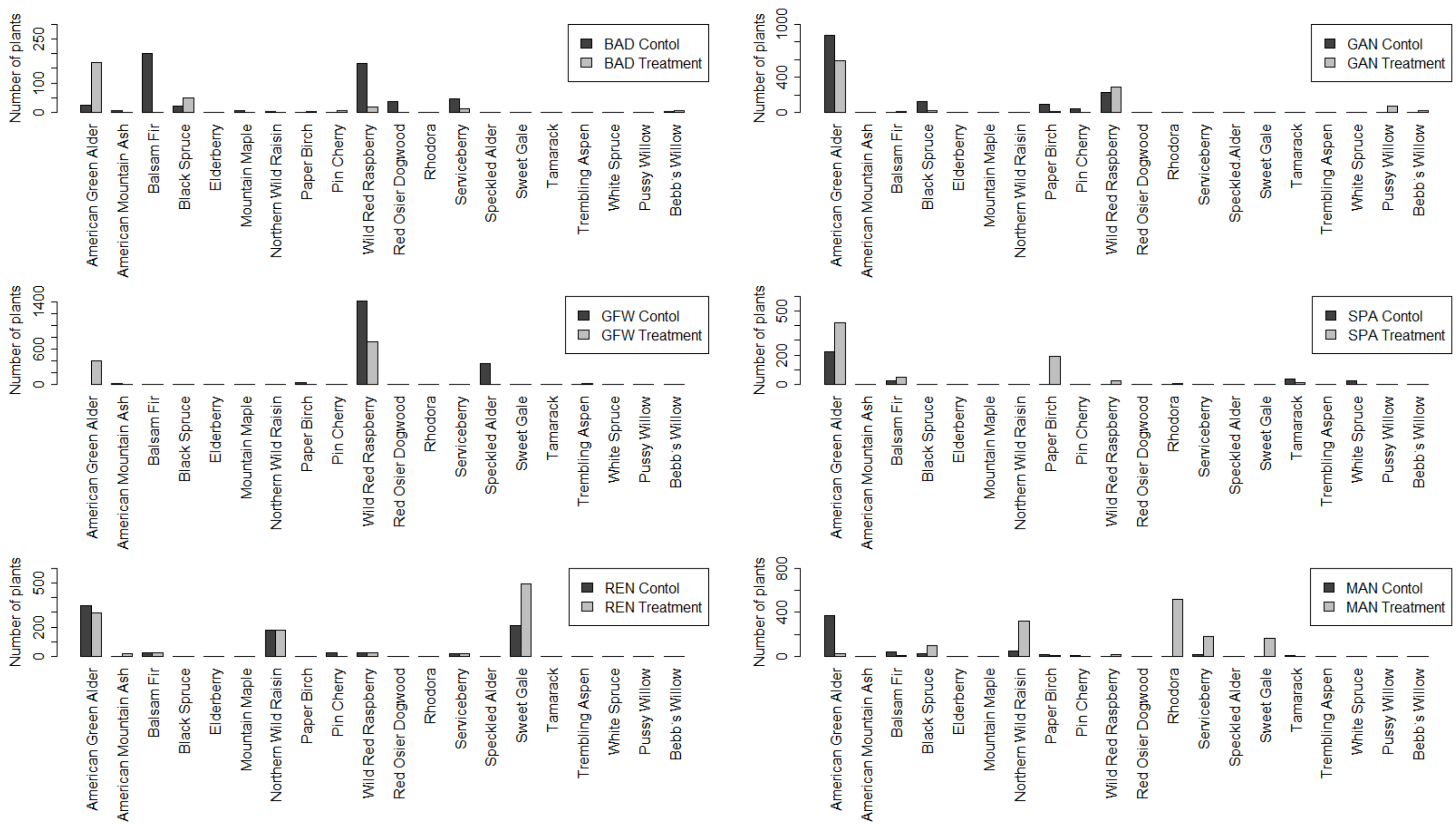

Figure A1-8: Displaying the number of individuals of preferred plants (according to Dodds, 1960) in each control (dark grey bars) and treatment (light grey bars) area within each site. It appears as though visually, depending on the species of plant, control and treatment areas were fairly evenly matched in terms of the number of preferred plants present.

References:

1. Dodds, D. G. (1960). Food competition and range relationships of moose and snowshoe hare in Newfoundland. *Journal of Wildlife Management, 24*(1), 52-60.

Table A1-9: Descriptive statistics of plant height in the sampling sites (CTRL: control – not cut since at least 2008, TRT 1: treatment 1 – cut between 2008-2010, and TRT 2: treatment 2 – cut between 2011-2013) in Newfoundland. The chart provides an overview of the structure of the plant community, including the proportion of plants in three height categories, and one combined category. The distinction at 30cm was made because moose rarely browse below this height (Wam and Hjeljord, 2010).

	CTRL	TRT 1	TRT 2
Percent of plants >200 cm	8.10	2.59	0.27
Percent of plants 30-200 cm	59.12	50.18	48.84
Percent of plants <30 cm	32.78	47.23	50.90
Percent of plants 30-200 cm and >200 cm	67.22	52.77	49.10

References:

1. Wam, H. K., & Hjeljord, O. (2010). Moose summer diet from feces and field surveys: a comparative study. *Rangeland Ecology & Management, 63*(3), 387-395. doi: 10.2111/Rem-D-09-00039.1

Appendix 2 (A2): Chapter 3 Additional Data and Results

In this appendix we present additional information on the small spatial grain hotspot analysis, buffer sizes, variable descriptions, and model results for the spatial correlates of moose-vehicle collisions in Newfoundland.

SANET may be more appropriate for analyzing the density of points along a linear network because it does not include surrounding areas in its analysis. Unfortunately, we were unable to run the SANET kernel density estimation at all of our desired bandwidths due to insufficient computing power, resulting from the large spatial grain of our analysis. However, since the two processes identified similar hotspots at the small spatial grain, it appears that qualitatively our ArcMap kernel density analysis is comparable to the SANET kernel density and is therefore sufficient for identifying hotspots at the larger bandwidth sizes.

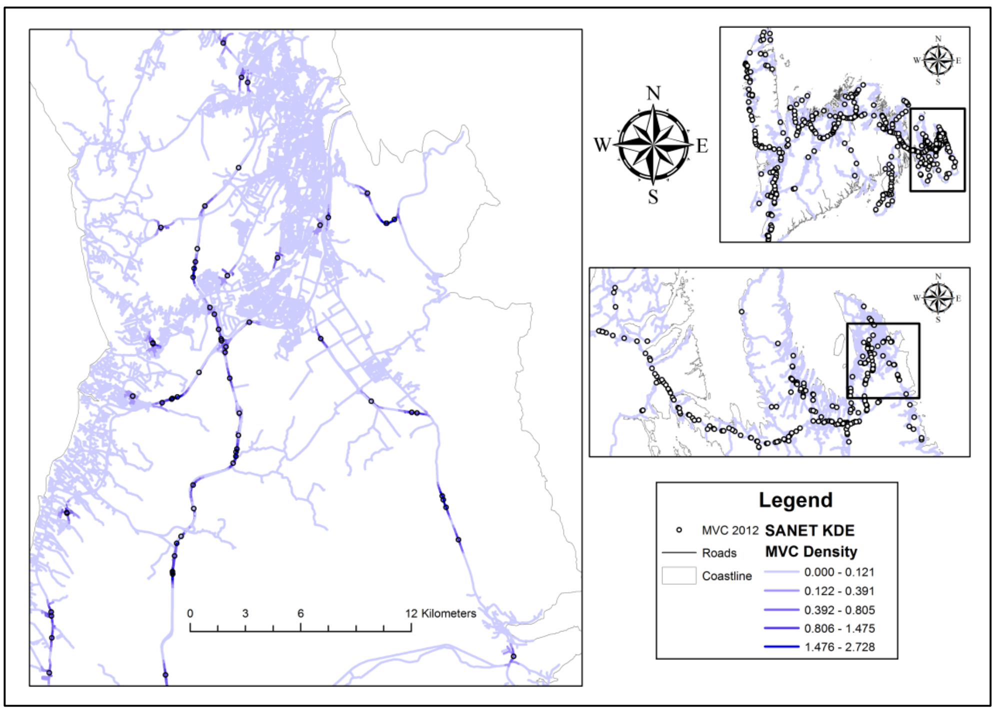

Figure A2-1: Map displaying the hotspots located using kernel density estimation at a 1km bandwidth with the SANET V4.1 toolbox add-on to ArcMap. This tool analyzes MVC density along the road network itself rather than also including the surrounding areas. The darker the purple, the higher the density of MVCs. The grey outlined circles designate MVC locations for 2012 and the linear light grey features indicate the road network of Newfoundland.

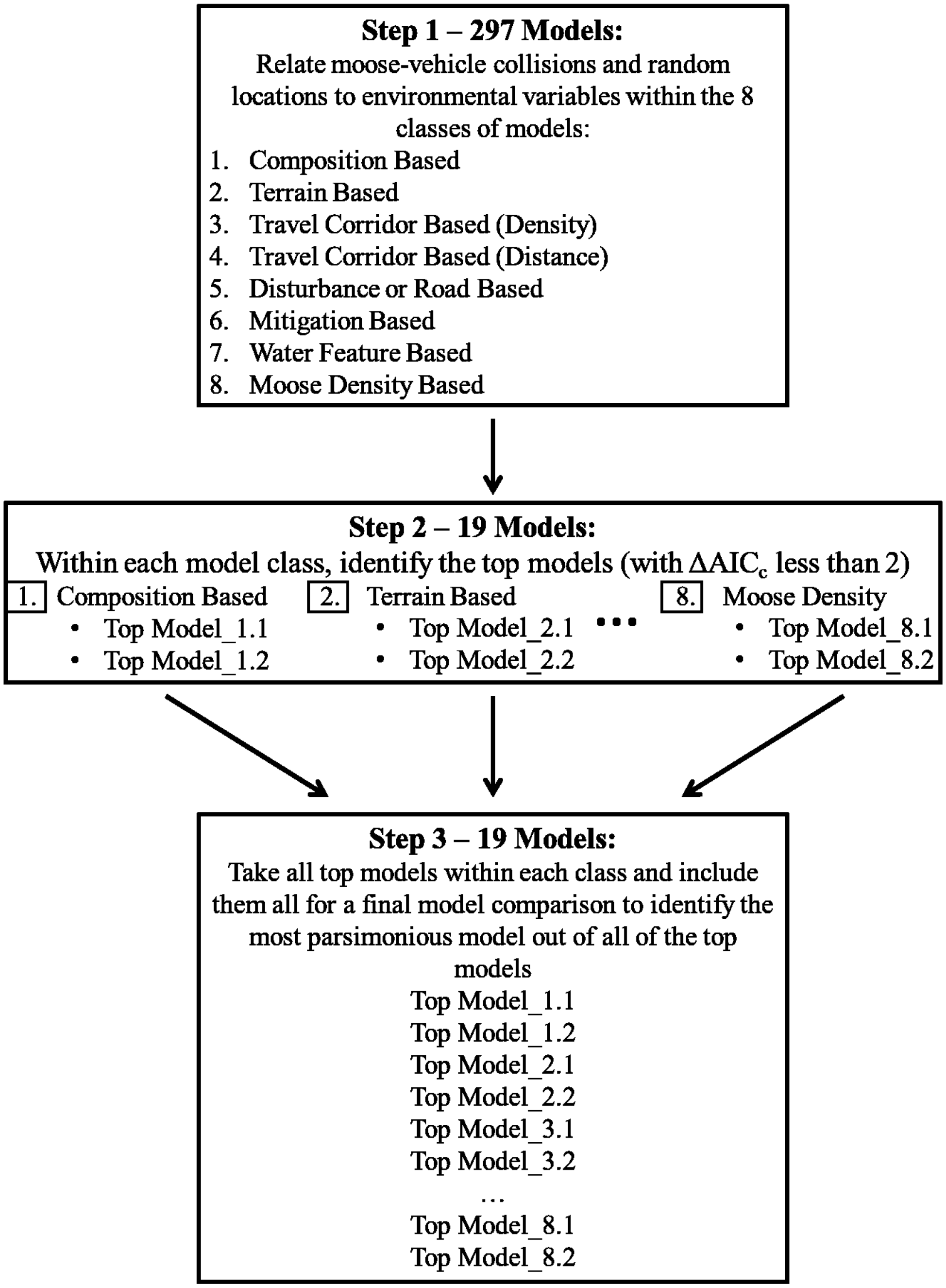

Figure A2-2: Flow diagram displaying the steps followed in our model selection analysis, conducted to determine the top model out of all of the competing models.

Table A2-3: Summary information for the moose collar data used to determine the medium (2,736m radius), and large (5,471m radius) buffer sizes including year the animal was collared, gender, capture age, and home range as estimated from a minimum convex polygon of the collar data. The collar data were obtained from the Department of Environment and Conservation – Wildlife Division and were collected on the Northern Peninsula near highway 432 and in central Newfoundland between Buchans, Howley, and South Brook.

Moose ID	**Year collared**	**Gender**	**Capture Age**	**Home Range (km^2)**
001	2010	Female	Adult	93.06
002	2010	Female	Adult	221.98
003	2010	Female	Adult	128.69
004	2010	Female	Adult	156.16
005	2010	Female	Adult	93.30
006	2010	Female	Adult	52.54
007	2010	Female	Adult	36.69
008	2010	Female	Young Adult	274.62
009	2010	Male	Adult	151.11
010	2011	Female	Adult	183.54
011	2011	Female	Calf	28.58
012	2011	Female	Adult	55.71
013	2011	Female	Calf	18.05
014	2011	Female	Adult	17.26
015	2011	Female	Adult	36.43
016	2011	Male	Calf	64.17
017	2011	Male	Adult	49.63
018	2011	Male	Adult	30.94
			Total	1692.48
			Mean	94.03
			Standard Deviation	75.89
			Radius	5.47

Table A2-4: Explanation of the abbreviated variable names used in the models.

Model Class	Variable Abbreviation	Definition
500m composition based models	1. PropDecid500 2. PropConif500 3. PropWater500 4. PropDev500 5. PropGrass500 6. PropShrub500 7. PropBare500	1. Proportion of deciduous-mixed forest (500m buffer) 2. Proportion of coniferous-needleleaved deciduous forest (500m buffer) 3. Proportion of open water/ regularly flooded areas (500m buffer) 4. Proportion of developed areas (500m buffer) 5. Proportion of grassland (500m buffer) 6. Proportion of shrubland (500m buffer) 7. Proportion of sparse vegetation/ bare areas (500m buffer)
2736m composition based models	1. PropDecid2736 2. PropConif2736 3. PropWater2736 4. PropDev2736 5. PropGrass2736 6. PropShrub2736 7. PropBare2736	1. Proportion of deciduous-mixed forest (2736m buffer) 2. Proportion of coniferous-needleleaved deciduous forest (2736m buffer) 3. Proportion of open water/ regularly flooded areas (2736m buffer) 4. Proportion of developed areas (2736m buffer) 5. Proportion of grassland (2736m buffer) 6. Proportion of shrubland (2736m buffer) 7. Proportion of sparse vegetation/ bare areas (2736m buffer)
5471m composition based models	1. PropDecid5471 2. PropConif5471 3. PropWater5471 4. PropDev5471 5. PropGrass5471 6. PropShrub5471 7. PropBare5471	1. Proportion of deciduous-mixed forest (5471m buffer) 2. Proportion of coniferous-needleleaved deciduous forest (5471m buffer) 3. Proportion of open water/ regularly flooded areas (5471m buffer) 4. Proportion of developed areas (5471m buffer) 5. Proportion of grassland (5471m buffer) 6. Proportion of shrubland (5471m buffer) 7. Proportion of sparse vegetation/ bare areas (5471m buffer)
Terrain based models	1. Aspect	1. Aspect 2. Mean slope (500m buffer)

	2. Slope_mean500 3. TerrRugg500 4. Slope_mean2736 5. TerrRugg2736 6. Slope_mean5471 7. TerrRugg5471	3. Mean terrain ruggedness (500m buffer) 4. Mean slope (2736m buffer) 5. Mean terrain ruggedness (2736m buffer) 6. Mean slope (5471m buffer) 7. Mean terrain ruggedness (5471m buffer)
Travel corridor (density) based models	1. DenFAR500 2. DenTL500 3. DenRW500 4. DenTR500 5. DenFAR2736 6. DenTL2736 7. DenRW2736 8. DenTR2736 9. DenFAR5471 10. DenTL5471 11. DenRW5471 12. DenTR5471	1. Density of forest access roads (500m buffer) 2. Density of transmission lines (500m buffer) 3. Density of decommissioned railways (500m buffer) 4. Density of trails (500m buffer) 5. Density of forest access roads (2736m buffer) 6. Density of transmission lines (2736m buffer) 7. Density of decommissioned railways (2736m buffer) 8. Density of trails (2736m buffer) 9. Density of forest access roads (5471m buffer) 10. Density of transmission lines (5471m buffer) 11. Density of decommissioned railways (5471m buffer) 12. Density of trails (5471m buffer)
Travel corridor (distance) based models	1. DisFAR_m 2. DisTL_m 3. DisRW_m 4. DisTR_m	1. Distance to forest access roads in meters 2. Distance to transmission lines in meters 3. Distance to decommissioned railways in meters 4. Distance to trails in meters
Disturbance or road based models	1. DisDevA_m 2. DisDevL_m 3. DisDevM_m 4. DisDevS_m 5. DisMA_m 6. RdClass 7. Sinuosity	1. Distance to developed areas (all sizes) in meters 2. Distance to developed areas (large) in meters 3. Distance to developed areas (medium) in meters 4. Distance to developed areas (small) in meters

		5. Distance to mining areas in meters 6. Road classification (primary or secondary) 7. Road tortuosity
Mitigation based models	1. VegCtLoc	1. Presence or absence or vegetation cutting locations
Water feature based models	1. DisOcn_m 2. DisWet_m 3. DisRiv_m 4. DisLak_m	1. Distance to ocean in meters 2. Distance to wetlands in meters 3. Distance to rivers in meters 4. Distance to lakes in meters
Moose density based models	1. MooseDen	1. Density of moose in number of moose/km^2

Table A2-5: Results of the AIC_c analysis for the candidate set of models from the 500m composition based models buffer group with ΔAIC_c less than two (see Table A2-4 for variable definitions).

Model	**k[a]**	**Fixed effects**	**AIC_c[a]**	**ΔAIC_c[a]**	**ωAIC_c[a]**	**LL[a]**	**R^2[a]**
Comp500A8	6	PropConif500 + PropWater500 + PropDev500 + PropGrass500 + PropShrub500	3321.15	0	0.36	-1654.56	0.02
Comp500A24	5	PropConif500 + PropWater500 + PropDev500 + PropGrass500	3323.12	1.97	0.13	-1656.55	0.02

[a] Key: k, number of parameters; AIC_c, Akaike Information Criterion corrected for small sample size; ΔAIC_c, the difference in the AIC_c; ωAIC_c, model weights; LL, log-likelihood; R^2, Nagelkerke's R^2.

Table A2-6: Results of the AIC_c analysis for the candidate set of models from the 2736m composition based models buffer group with ΔAIC_c less than two (see Table A2-4 for variable definitions).

Model	**k[a]**	**Fixed effects**	**AIC_c[a]**	**ΔAIC_c[a]**	**ωAIC_c[a]**	**LL[a]**	**R^2[a]**
Comp2736A30	5	PropConif2736 + PropDev2736 + PropGrass2736 + PropShrub2736	3317.12	0	0.54	-1653.55	0.02

[a] Key: k, number of parameters; AIC_c, Akaike Information Criterion corrected for small sample size; ΔAIC_c, the difference in the AIC_c; ωAIC_c, model weights; LL, log-likelihood; R^2, Nagelkerke's R^2.

Table A2-7: Results of the AIC_c analysis for the candidate set of models from the 5471m composition based models buffer group with ΔAIC_c less than two (see Table A2-4 for variable definitions).

Model	**k[a]**	**Fixed effects**	**AIC_c[a]**	**ΔAIC_c[a]**	**ωAIC_c[a]**	**LL[a]**	**R^2[a]**
Comp5471A12	6	PropConif5471 + PropDev5471 + PropGrass5471 + PropShrub5471 + PropBare5471	3311.31	0	0.27	-1649.65	0.02
Comp5471A30	5	PropConif5471 + PropDev5471 + PropGrass5471 + PropShrub5471	3311.89	0.58	0.20	-1650.94	0.02
Comp5471A6	6	PropDecid5471 + PropConif5471 + PropDev5471 + PropGrass5471 + PropShrub5471	3312.18	0.87	0.17	-1650.08	0.02
Comp5471A1	7	PropDecid5471 + PropConif5471 + PropWater5471 + PropDev5471 + PropGrass5471 + PropShrub5471	3312.65	1.34	0.14	-1649.31	0.02

[a] Key: k, number of parameters; AIC_c, Akaike Information Criterion corrected for small sample size; ΔAIC_c, the difference in the AIC_c; ωAIC_c, model weights; LL, log-likelihood; R^2, Nagelkerke's R^2.

Table A2-8: Results of the AIC_c analysis for the candidate set of models from the terrain based models group with ΔAIC_c less than two (see Table A2-4 for variable definitions).

Model	**k[a]**	**Fixed effects**	**AIC_c[a]**	**ΔAIC_c[a]**	**ωAIC_c[a]**	**LL[a]**	**R^2[a]**
Terrain7	2	TerrRugg500	3321.67	0	0.32	-1658.83	0.01
Terrain1	3	TerrRugg500 + Aspect	3322.40	0.73	0.22	-1658.20	0.01
Terrain11	2	Slope_mean500	3322.44	0.77	0.21	-1659.22	0.01
Terrain4	3	Slope_mean500 + Aspect	3323.34	1.67	0.14	-1658.67	0.01

[a] Key: k, number of parameters; AIC_c, Akaike Information Criterion corrected for small sample size; ΔAIC_c, the difference in the AIC_c; ωAIC_c, model weights; LL, log-likelihood; R^2, Nagelkerke's R^2.

Table A2-9: Results of the AIC_c analysis for the candidate set of models from the travel corridor (density) based models group with ΔAIC_c less than two (see Table A2-4 for variable definitions).

Model	**k[a]**	**Fixed effects**	**AIC_c[a]**	**ΔAIC_c[a]**	**ωAIC_c[a]**	**LL[a]**	**R^2[a]**
TravelDen2	5	DenFAR2736 + DenRW2736 + DenTL2736 + DenTR2736	3146.67	0	0.79	-1568.33	0.09

[a] Key: k, number of parameters; AIC_c, Akaike Information Criterion corrected for small sample size; ΔAIC_c, the difference in the AIC_c; ωAIC_c, model weights; LL, log-likelihood; R^2, Nagelkerke's R^2.

Table A2-10: Results of the AIC_c analysis for the candidate set of models from the travel corridor (distance) based models group with ΔAIC_c less than two (see Table A2-4 for variable definitions).

Model	**k**[a]	**Fixed effects**	**AIC_c**[a]	**ΔAIC_c**[a]	**ωAIC_c**[a]	**LL**[a]	**R^2**[a]
TravelDist7	3	DisTL_m + DisTR_m	3264.03	0	0.53	-1629.01	0.04
TravelDist2	4	DisFAR_m+ DisTL_m + DisTR_m	3264.25	0.22	0.47	-1628.12	0.04

[a] Key: k, number of parameters; AIC_c, Akaike Information Criterion corrected for small sample size; ΔAIC_c, the difference in the AIC_c; ωAIC_c, model weights; LL, log-likelihood; R^2, Nagelkerke's R^2.

Table A2-11: Results of the AIC_c analysis for the candidate set of models from the disturbance or road based models group with ΔAIC_c less than two (see Table A2-4 for variable definitions).

Model	**k**[a]	**Fixed effects**	**AIC_c**[a]	**ΔAIC_c**[a]	**ωAIC_c**[a]	**LL**[a]	**R^2**[a]
Road6	5	RdClass + Sinuosity + DisMA_m + DisDevL_m	2609.98	0	0.99	-1299.98	0.30

[a] Key: k, number of parameters; AIC_c, Akaike Information Criterion corrected for small sample size; ΔAIC_c, the difference in the AIC_c; ωAIC_c, model weights; LL, log-likelihood; R^2, Nagelkerke's R^2.

Table A2-12: Results of the AIC_c analysis for the candidate set of models from the mitigation based models group with ΔAIC_c less than two (see Table A2-4 for variable definitions).

Model	**k[a]**	**Fixed effects**	**AIC_c[a]**	**ΔAIC_c[a]**	**ωAIC_c[a]**	**LL[a]**	**R^2[a]**
Mitigation1	2	VegCtLoc	3138.68	0	1	-1567.34	0.09

[a] Key: k, number of parameters; AIC_c, Akaike Information Criterion corrected for small sample size; ΔAIC_c, the difference in the AIC_c; ωAIC_c, model weights; LL, log-likelihood; R^2, Nagelkerke's R^2.

Table A2-13: Results of the AIC_c analysis for the candidate set of models from the water feature based models group with ΔAIC_c less than two (see Table A2-4 for variable definitions).

Model	**k**[a]	**Fixed effects**	**AIC_c**[a]	**ΔAIC_c**[a]	**ωAIC_c**[a]	**LL**[a]	**R^2**[a]
WaterFeat1	5	DisRiv_m + DisWet_m + DisOcn_m + DisLak_m	3308.55	0	0.92	-1649.27	0.02

[a] Key: k, number of parameters; AIC_c, Akaike Information Criterion corrected for small sample size; ΔAIC_c, the difference in the AIC_c; ωAIC_c, model weights; LL, log-likelihood; R^2, Nagelkerke's R^2.

Table A2-14: Results of the AIC_c analysis for the candidate set of models from the moose density based models group with ΔAIC_c less than two (see Table A2-4 for variable definitions).

Model	**k[a]**	**Fixed effects**	**AIC_c[a]**	**ΔAIC_c[a]**	**ωAIC_c[a]**	**LL[a]**	**R^2[a]**
MooseDensity1	2	MooseDen	3347.11	0	1	-1671.55	0.002

[a] Key: k, number of parameters; AIC_c, Akaike Information Criterion corrected for small sample size; ΔAIC_c, the difference in the AIC_c; ωAIC_c, model weights; LL, log-likelihood; R^2, Nagelkerke's R^2.

Table A2-15: Results of the AIC_c analysis for the across model class comparison candidate set of models with ΔAIC_c less than two (see Table A2-4 for variable definitions). We used an intercept only model as the null model to ascertain if adding additional fixed effects improved the AIC_c.

Model	**k[a]**	**AIC_c[a]**	**ΔAIC_c[a]**	**ωAIC_c[a]**	**LL[a]**	**R^2[a]**
Road6	5	2609.98	0	1	-1299.98	0.30
Mitigation1	2	3138.68	528.70	0	-1567.34	0.09
TravelDen2	5	3146.67	536.69	0	-1568.33	0.09
TravelDist7	3	3264.03	654.05	0	-1629.01	0.04
TravelDist2	4	3264.25	654.27	0	-1628.12	0.04
WaterFeat1	5	3308.55	698.58	0	-1649.27	0.02
Comp5471A12	6	3311.31	701.34	0	-1649.65	0.02
Comp5471A30	5	3311.89	701.91	0	-1650.94	0.02
Comp5471A6	6	3312.18	702.21	0	-1650.08	0.02
Comp5471A1	7	3312.65	702.67	0	-1649.31	0.02
Comp2736A30	5	3317.12	707.15	0	-1653.55	0.02
Comp500A8	6	3321.15	711.17	0	-1654.56	0.02
Terrain7	2	3321.67	711.70	0	-1658.83	0.01
Terrain1	3	3322.40	712.42	0	-1658.20	0.01
Terrain11	2	3322.44	712.46	0	-1659.22	0.01
Comp500A24	5	3323.12	713.14	0	-1656.55	0.02
Terrain4	3	3323.34	713.37	0	-1658.67	0.01
MooseDensity1	2	3347.11	737.13	0	-1671.55	0.00
Null	1	3349.38	739.41	0	-1673.69	0.00

[a] Key: k, number of parameters; AIC_c, Akaike Information Criterion corrected for small sample size; ΔAIC_c, the difference in the AIC_c; ωAIC_c, model weights; LL, log-likelihood; R^2, Nagelkerke's R^2.

Table A2-16: Results of the K-fold cross-validation analysis for the across model class comparison of models with ΔAIC_c less than two (null model is not included).

Model ΔAIC_c<2	**Adjusted Cross-Validation Estimate of Error**
Road 6	0.1543631
Mitigation 1	0.1540041
TravelDen2	0.1533625
TravelDist7	0.1540041
TravelDist2	0.1540041
WaterFeat1	0.1540041
Comp5471A12	0.1540041
Comp5471A30	0.1540041
Comp5471A6	0.1540041
Comp5471A1	0.1540041
Comp2736A30	0.1540041
Comp500A8	0.1540041
Terrain7	0.1540041
Terrain1	0.1540041
Terrain11	0.1540041
Comp500A24	0.1540041
Terrain4	0.1540041
MooseDensity1	0.1540041